SPECIAL COLLECTOR'S EDITION

SCIENTIFIC AMERICAN

THE AGE OF HUMANS

Where we came from, the world we've created and where we're going

INSIDE

- Our mark on Earth
- The story of our evolution
- How long will humans last?
- The legacy of the Anthropocene
- New ways to live more sustainably
- An AI revolution that will change everything

FALL 2021

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FROM THE EDITOR

The Story of Us

It has never been a given that humans would survive on Earth. We have likely faced extinction several times in our evolutionary past, according to genetic analysis. The ease with which the novel coronavirus has swept around the planet reminds us that there are no guarantees. And yet we are a species to be reckoned with. We have accomplished a great deal in our relatively short history—extended our life spans, discovered vast knowledge about our world and ourselves, harnessed resources to improve quality of life, and developed rich histories of art and culture. For better or worse, the human legacy on Earth is unparalleled.

How did we get here? It turns out that our evolutionary story is not a linear progression from ape ancestor to human. Each fossil discovery is a knot in a messy tangle of evolution that led to *Homo sapiens* (*page 4*). Our large brains helped to solve the complex test of primitive survival (*page 10*), and interpersonal relationships and altruism may have given us a strong advantage over other hominins (*page 14*). And such development is far from over: modern humans continue to adapt to our changing world, even if we often feel that we have somehow bested natural selection (*page 22*).

WEST BENGAL train station during the global COVID pandemic.

And what a world we've made. We have built a behemoth of financial systems, global communication and trade networks, and information technology (*page 56*). The benefits of those systems are not evenly distributed, leaving many lacking basic resources and health care (*page 36*). And now some economists have started to wonder if we are using the proper tools to measure the value of a society (*page 28*). To be sure, our life expectancy has more than tripled over the course of our two-million-year story. At the same time a rapidly warming world, increased land use and growing inequality will undoubtedly give rise to new threats to health and longevity (*page 42* and *48*).

Human progress has had measurable effects on the planet, even down to the layers of concrete, plastics and nuclear waste we leave behind—indelible enough, perhaps, to mark a new geologic era (*page 68*). A drastically changing climate will require bold action and adaptation on our part (*page 82*), including tackling the disproportionate impact that environmental degradation has on the world's poor and oppressed peoples (*page 76*).

The ingenuity that launched us to the top of the evolutionary food chain could also fast-track major improvements for life on Earth. Cities, which house more than half the global population, might become the hotbeds of sustainable solutions that cut down on both resource consumption and pollution (*page 108*). And local and rural communities that manage their own food production and wealth could end up more self-sufficient and in harmony with the natural world (*page 88*).

Of course, this story is far from over. If we make the right decisions now, the next era on Earth might be named the Sapiezoic, or "wise life" (*page 112*). Such a time would be characterized by sustainable prosperity and peace afforded to all people and fueled by that distinct tenacious creativity that is undeniably human.

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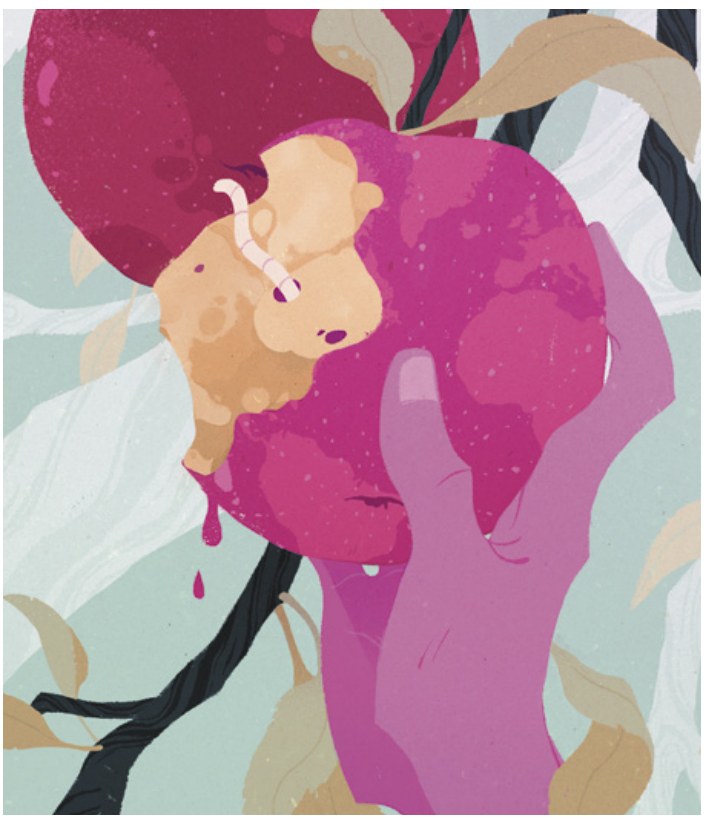

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A popular name for our era perpetuates misperceptions about humans and nature. *By the Editors*

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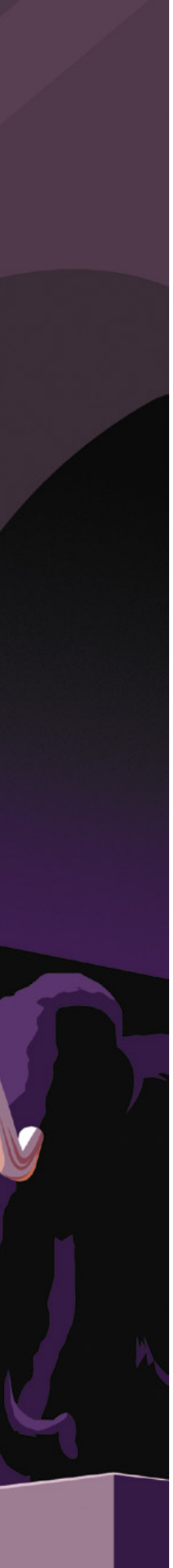

THE ORIGIN *of* US

Fossils and DNA have revealed the complexity of human evolution. Darwin would be delighted

By Kate Wong

Illustration by Pascal Blanchet

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IN 1859, 14 YEARS AFTER THE FOUNDING OF THIS MAGAZINE, CHARLES DARWIN PUBLISHED the most important scientific book ever written. *On the Origin of Species* revolutionized society's understanding of the natural world. Challenging Victorian dogma, Darwin argued that species were not immutable, each one specially created by God. Rather life on Earth, in all its dazzling variety, had evolved through descent from a common ancestor with modification by means of natural selection. But for all of Darwin's brilliant insights into the origins of ants and armadillos, bats and barnacles, one species is conspicuously neglected in the great book: his own. Of *Homo sapiens,* Darwin made only a passing mention on the third-to-last page of the tome, noting coyly that "light will be thrown on the origin of man and his history." That's it. That is all he wrote about the dawning of the single most consequential species on the planet.

It was not because Darwin thought humans were somehow exempt from evolution. Twelve years later he published a book devoted to that very subject, *The Descent of Man*. In it, he explained that discussing humans in his earlier treatise would have served only to further prejudice readers against his radical idea. Yet even in this later work, he had little to say about human origins per se, instead focusing on making the case from comparative anatomy, embryology and behavior that, like all species, humans had evolved. The problem was that there was hardly any fossil record of humans at that time to provide evidence of earlier stages of human existence. Back then, "the only thing you knew was what you could reason," says paleoanthropologist Bernard Wood of the George Washington University.

To his credit, Darwin made astute observations about our kind and predictions about our ancient past based on the information that was available to him. He argued that all living humans belong to one species and that its "races" all descended from a single ancestral stock. And pointing to the anatomical similarities between humans and African apes, he concluded that chimpanzees and gorillas were the closest living relatives of humans. Given that relationship, he figured, early human ancestors probably lived in Africa.

Since then, Wood says, "the evidence has come in." In the past century and a half, science has confirmed Darwin's prediction and pieced together a detailed account of our origins. Paleoanthropologists have recovered fossil hominins (the group that comprises *H. sapiens* and its extinct relatives) spanning the past seven million years. This extraordinary record shows that hominins indeed got their start in Africa, where they evolved from quadrupedal apes into the upright-walking, nimble-fingered, large-brained creatures we are today.

And the archaeological record of hominin creations, which encompasses roughly half that time, charts their cultural evolution—from early experiments with simple stone tools to the invention of symbols, songs and stories—and maps our ancestors' spread across the globe. The fossils and artifacts demonstrate that for most of the period over which our lineage has been evolving, multiple hominin species walked the earth. Studies of modern and ancient DNA have generated startling insights into what happened when they encountered one another.

The human saga, we now understand, is far more intricate than scholars of yore envisioned. The tidy tropes of our prehistory have collapsed under the weight of evidence: there is no single missing link that bridges apes and humankind, no drumbeat march of progress toward a predestined goal. Our story is complicated, messy and random. Yet it still can be accommodated under Darwin's theory of evolution and in fact further validates that framework.

This is not to say scientists have it all figured out. Many questions remain. But whereas the origin of humans was once an uncomfortable speculation in Darwin's big idea, it is now among the best-documented examples of evolution's transformative power.

WE HUMANS ARE STRANGE CREATURES. We walk upright on two legs and possess supersized brains, we invent tools to meet our every need and express ourselves using symbols, and we have conquered every corner of the planet. For centuries scientists have sought to explain how we came to be, our place in the natural world.

This quest was often distorted by racist ideologies. Consider the era leading up to the birth of Darwin's bombshell theory. In the 1830s, while a young Darwin was making his momentous voyage onboard the *Beagle,* a movement was underway to promote the idea that the various modern human groups around the globe—races—had separate origins. To build the case for polygenism, as the theory is known, scientists such as Samuel Morton in Philadelphia collected skulls from people across the world and measured their sizes and shapes, falsely believing those attributes to be proxies for intelligence. When they ranked the specimens from superior to inferior, Europeans would conveniently come out on top and Africans on the bottom. "There was a desire to provide scientific justification for political and power structures," says anthropological geneticist Jennifer Raff of the University of Kansas. "It was science in the service of slavery and colonialism."

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NEANDERTALS were the first extinct hominin species to be recognized in the fossil record and the first to yield ancient DNA.

Javier Trueba *Science Source*

Although Darwin's work came down firmly on the side of monogenism—the idea that all humans share a common ancestor—it was nonetheless co-opted to support notions about racial superiority. Social Darwinism, for one, misapplied Darwin's ideas about the struggle for existence in natural selection to human society, providing a pseudoscientific rationalization for social injustice and oppression. Darwin himself did not subscribe to such views. In fact, his opposition to slavery may have been a driving force in his research agenda, according to his biographers Adrian Desmond and James Moore.

By the time Darwin published *The Descent of Man,* in 1871, the idea that humans had evolved from a common ancestor with apes was already gaining traction in the scientific community thanks to books published in the 1860s by English biologist Thomas Henry Huxley and Scottish geologist Charles Lyell. Still, the fossil evidence to support this claim was scant. The only hominin fossils known to science were a handful of remains a few tens of thousands of years old that had been recovered from sites in Europe. Some were *H. sapiens;* others would eventually be recognized as a separate but very closely related species, *Homo neanderthalensis*. The implication was that fossils of more apelike human ancestors were out there somewhere in the world, awaiting discovery. But the suggestion by Darwin, like Huxley before him, that those ancestors would be found in Africa met with resistance from scholars who saw Asia as a more civilized birthplace for humankind and emphasized similarities between humans and Asia's gibbons.

Perhaps it should come as no surprise, then, that when the first hominin fossil significantly older and more primitive than those from Europe turned up, it came not from Africa but from Asia. In 1891 Dutch anatomist Eugène Dubois discovered remains on the Indonesian island of Java that he thought belonged to the long-sought missing link between apes and humans. The find, which he named *Pithecanthropus erectus,* spurred further efforts to root humankind in Asia. (We now know that Dubois's fossil was between 700,000 and one million years old and belonged to a hominin that was much more humanlike than apelike, *Homo erectus*.)

Two decades later the search turned to Europe. In 1912 amateur archaeologist Charles Dawson reported that he had found a skull with a humanlike cranium and an apelike jaw in an ancient gravel pit near the site of Piltdown in East Sussex, England. Piltdown Man, as the specimen was nicknamed, was a leading contender for the missing link until it was exposed in 1953 as a fraudulent pairing of a modern human skull with an orangutan's lower jaw.

Piltdown so seduced scholars with the prospect of making Europe the seat of human origins that they all but ignored an actual ancient hominin that turned up in Africa, one even older and more apelike than the one Dubois discovered. In 1925, 43 years after Darwin's death, anatomist Raymond Dart published a paper describing a fossil from Taung, South Africa, with an apelike braincase and humanlike teeth. Dart named that fossil—a youngster's skull now known to be around 2.8 million years old—*Australopithecus africanus,* "the southern ape from Africa." But it would take nearly 20 years for the scientific establishment to accept Dart's argument that the so-called Taung Child was of immense significance: the fossil linked humans to African apes.

Evidence of humanity's African origins has accumulated ever since. Every hominin trace older than 2.1 million years—and there are now quite a few of them—has come from that continent.

EVEN AS FOSSIL DISCOVERIES proved Darwin right about the birthplace of humanity, the pattern of our emergence remained elusive. Darwin himself depicted evolution as a branching process in which ancestral species divide into two or more descendant species. But a long-standing tradition of organizing nature hierarchically—one that dates back to Plato and Aristotle's Great Chain of Being—held sway, giving rise to the notion that our evolution unfolded in linear fashion from simple to complex, primitive to modern. Popular imagery reflected and reinforced this idea, from a caricature in *Punch's Almanack* for 1882 showing a progression from earthworm to Darwin, to the iconic monkey-to-man illustration that appeared in the 1965 Time-Life book *Early Man* and became known as the March of Progress.

From the rich assortment of fossils and artifacts recovered from around the world in the past century, however, paleoanthropologists can now reconstruct something of the timing and pattern of human evolution. The finds clearly show that this single-file scheme is no longer tenable. Evolution does not march steadily toward predetermined goals. And many hominin specimens belong not in our direct line of ancestry but on side branches of humankind—evolutionary experiments that ended in extinction.

From the outset, our defining traits evolved not in lockstep but piecemeal. Take our mode of locomotion, for example. *H. sapiens* is what anthropologists call an obligate biped—our bodies

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are built for walking on two legs on the ground. We can climb trees if we need to, but we have lost the physical adaptations that other primates have to arboreal life. Fragmentary fossils of the oldest known hominins—*Sahelanthropus tchadensis* from Chad, *Orrorin tugenensis* from Kenya and *Ardipithecus kadabba* from Ethiopia—show that our earliest ancestors emerged by around seven million to 5.5 million years ago. Although they are apelike in many respects, all of them exhibit characteristics associated with walking on two legs instead of four. In *Sahelanthropus,* for example, the hole in the base of the skull through which the spinal cord passes has a forward position suggestive of an upright posture. A bipedal gait may thus have been one of the very first traits that distinguished hominins from ancestral apes.

Yet our forebears appear to have retained traits needed for arboreal locomotion for millions of years after they first evolved the ability to walk on two legs. *Australopithecus afarensis,* which lived in eastern Africa from 3.85 million to 2.95 million years ago and is famously represented by the skeleton known as Lucy, discovered in 1974, was a capable biped. But it had long, strong arms and curved fingers—features associated with tree climbing. It would be another million years before modern limb proportions evolved and committed hominins to life on the ground, starting with early *H. erectus* in Africa (sometimes called *Homo ergaster*).

The brain evolved on quite a different schedule. Over the course of human evolution, brain size has more than tripled. A comparison of the braincase of *A. afarensis* with that of the much older *Sahelanthropus,* however, shows that hardly any of that growth occurred in the first few million years of human evolution. In fact, most of the expansion took place in the past two million years, perhaps enabled by a feedback loop in which advances in technology—stone tools and the like—gave hominins access to more nutritious foods such as meat, which could fuel a larger and thus more energetically demanding brain, which in turn could dream up even better technology, and so on. Shifts in the shape and structure of the brain accompanied these gains, with more real estate allocated to regions involved in language and long-range planning, among other advanced cognitive functions.

This mosaic pattern of hominin evolution in which different body parts evolved at different rates produced some surprising creatures. For instance, *Australopithecus sediba* from South Africa, dated to 1.98 million years ago, had a humanlike hand attached to an apelike arm, a big birth canal but a small brain, and an advanced ankle bone connected to a primitive heel bone.

Sometimes evolution even doubled back on itself. When one examines a hominin fossil, it can be difficult to discern whether the species retained a primitive trait such as small brain size from an earlier ancestor or whether it lost the characteristic and then re-evolved it. But the strange case of *Homo floresiensis* may well be an example of the latter. This member of the human family lived on the island of Flores in Indonesia as recently as 50,000 years ago yet looked in many ways like some of the founding members of our genus who lived more than two million years earlier. Not only did *H. floresiensis* have a small body, but it also possessed a remarkably tiny brain for *Homo,* about the size of a chimp's. Scientists' best guess is that this species descended from a brawnier, brainer *Homo* species that got marooned on Flores and evolved its diminutive size as an adaptation to the limited food resources available on its island home. In so doing, *H. floresiensis* seems to have reversed what researchers once considered a defining trend of *Homo*'s evolution: the inexorable expansion of the brain. Yet despite its small brain, *H. floresiensis* still managed to make stone tools, hunt animals for food and cook over fires.

Adding to the complexity of our story, it is now clear that for most of the time over which humans have been evolving, multiple hominin species walked the earth. Between 3.6 million and 3.3 million years ago, for example, at least four varieties of hominins lived in Africa. Paleoanthropologist Yohannes Haile-Selassie of Arizona State University's Institute of Human Origins and his colleagues have recovered remains of two of them, *A. afarensis* and *Australopithecus deyiremeda,* as well as a possible third creature known only from a distinctive fossil foot, in an area called Woranso-Mille in Ethiopia's Afar region. How they managed to share the landscape is a subject of current investigation. "Competing species could co-exist if there were plenty of resources or if they were exploiting different parts of the ecosystem," Haile-Selassie says.

Later, between roughly 2.7 million and 1.2 million years ago, representatives of our genus, *Homo*—large-brained tool users with dainty jaws and teeth—shared the grasslands of southern and eastern Africa with a radically different branch of humanity. Members of the genus *Paranthropus,* these hominins had massive teeth and jaws, flaring cheek bones and crests atop their heads that anchored powerful chewing muscles. Here the co-existence is somewhat better understood: whereas *Homo* seems to have evolved to exploit a wide variety of plants and animals for food, *Paranthropus* specialized in processing tough, fibrous plant foods.

H. sapiens overlapped with other kinds of humans, too. When our species was evolving in Africa 300,000 years ago, several other kinds of hominins also roamed the planet. Some, such as the stocky Neandertals in Eurasia, were very close relatives. Others, including *Homo naledi* in South Africa and *H. erectus* in Indonesia, belonged to lineages that diverged from ours in the deep past. Even as recently as 50,000 years ago, hominin diversity was the rule, with the Neandertals, the mysterious Denisovans from Asia, tiny *H. floresiensis* and another small hominin—the recently discovered *Homo luzonensis* from the Philippines—all at large.

SUCH DISCOVERIES MAKE FOR A MUCH more interesting picture of human evolution than the linear account that has dominated our view of life. But they raise a nagging question: How did *H. sapiens* end up being the sole surviving twig on what was once a luxuriant evolutionary bush?

Here are the facts of the case. We know from fossils found at the site of Jebel Irhoud in Morocco that our species originated in Africa by at least 315,000 years ago. By around 200,000 years ago it began making forays out of Africa, and by 40,000 years ago it had established itself throughout Eurasia. Some of the places *H. sapiens* colonized were occupied by other hominin species. Eventually the other folks all disappeared. By around 30,000 to 15,000 years ago, with the end of the Neandertals in Europe and the Denisovans in Asia, *H. sapiens* was alone in the world.

Researchers have often attributed the success of our species to superior cognition. Although the Neandertals actually had slightly larger brains than ours, the archaeological record seemed to indicate that only *H. sapiens* crafted specialized tools and used symbols, suggesting a capacity for language. Perhaps, the thinking went, *H. sapiens* won out by virtue of sharper foresight, better technology, more flexible foraging strategies and bigger social

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networks for support against hard times. Alternatively, some investigators have proposed, maybe *H. sapiens* waged war on its rivals, exterminating them directly.

But recent discoveries have challenged these scenarios. Neandertal technology, archaeologists have learned, was far more varied and sophisticated than previously thought. Neandertals, too, made jewelry and art, crafting pendants from shells and animal teeth and painting abstract symbols on cave walls. Moreover, they may not have been our only enlightened kin: a 500,000-year-old engraved shell from Java suggests that *H. erectus* also possessed symbolic thought. If archaic hominins had many of the same mental faculties as *H. sapiens,* why did the latter prevail?

The conditions under which *H. sapiens* got its start may have played a role. Fossil and archaeological data suggest that our species mostly stayed in Africa for the first couple of hundred thousand years of its existence. There, some experts argue, it evolved as a population of interconnected subgroups spread across the continent that split up and reunited again and again over millennia, allowing for periods of evolution in isolation followed by opportunities for interbreeding and cultural exchange. This evolutionary upbringing may have honed *H. sapiens* into an especially adaptable hominin. But that is not the whole story, as we now know from genetics.

Evolution does not march steadily toward predetermined goals.

Analyses of DNA have revolutionized the study of human evolution. Comparing the human genome with the genomes of the living great apes has shown conclusively that we are most closely related to chimpanzees and bonobos, sharing nearly 99 percent of their DNA. And large-scale studies of DNA from modern-day human populations across the globe have illuminated the origins of modern human variation, overturning the centuries-old notion that races are biologically discrete groups with separate origins. "There have never been pure populations or races," Raff says. Modern human variation is continuous, and most variation actually exists within populations rather than between them—the product of our demographic history as a species that originated in Africa with populations that mixed continuously as they migrated around the world.

More recently, studies of ancient DNA have cast new light on the world of early *H. sapiens* as it was when other hominin species were still running around. In the late 1990s geneticists began recovering small amounts of DNA from Neandertal and early *H. sapiens* fossils. Eventually they succeeded in getting entire genomes not only from Neandertals and early *H. sapiens* but also from Denisovans, who are known from just a few fragmentary fossils from Siberia and Tibet. By comparing these ancient genomes with modern ones, researchers have found evidence that our own species interbred with these other species. People today carry DNA from Neandertals and Denisovans as a result of these long-ago encounters. Other studies have found evidence of interbreeding between *H. sapiens* and unknown extinct hominins from Africa and Asia for whom we have no fossils but whose distinctive DNA persists.

Mating with other human species may have aided *H. sapiens'* success. Studies of organisms ranging from finches to oak trees have shown that hybridization with local species can help colonizing species flourish in novel environments by giving them useful genes. Although scientists have yet to figure out the functions of most of the genes people today carry from extinct hominins, they have pinpointed a few, and the results are intriguing. For instance, Neandertals gave *H. sapiens* immunity genes that may have helped our species fend off novel pathogens it encountered in Eurasia, and Denisovans contributed a gene that helped people adapt to high altitudes. *H. sapiens* may be the last hominin standing, but it got a leg up from its extinct cousins.

SCIENTISTS HAVE MANY MORE PIECES of the human-origins puzzle than they once did, but the puzzle is now vastly bigger than it was previously understood to be. Many gaps remain, and some may never close. Take the question of why we evolved such massive brains. At around 1,400 grams, the modern human brain is considerably larger than expected for a primate of our body size. "The singularity is why it's interesting—and why it's impossible to answer scientifically," Wood observes. Some experts have suggested that hominin brains ballooned as they adapted to climate fluctuations between wet and dry conditions, among other explanations. But the problem with trying to answer "why" questions about the evolution of our unique traits, Wood says, is that there is no way to evaluate the proposed explanations empirically. "There isn't a counterfactual. We can't go back to three million years ago and not change the climate."

Other mysteries may yield to further investigation, however. For example, we do not yet know what the last common ancestor of humans and the *Pan* genus that includes chimps and bonobos looked like. Genomic and fossil data suggest that the two lineages diverged between eight million and 10 million years ago—up to three million years before the oldest known hominin walked the earth—which means that paleoanthropologists may be missing a substantial chunk of our prehistory. And they have hardly any fossils at all of *Pan,* which has been evolving along its own path just as long as we have. Insights may come from a project currently underway in central Mozambique, where Susana Carvalho and René Bobe of the University of Oxford and their colleagues are hunting for fossil primates, including hominins, in sediments older than the ones that yielded *Sahelanthropus, Orrorin* and *Ardipithecus.*

Later stages of the human story are riddled with unknowns, too. If *H. sapiens* was interbreeding with the other hominin species it encountered, as we now know it was, were these groups also exchanging culture? Might *H. sapiens* have introduced Neandertals to novel hunting technology and artistic traditions—or vice versa? New techniques for retrieving ancient DNA and proteins from otherwise unidentifiable fossils and even cave sediments are helping researchers determine which hominin species were active and when at key archaeological sites.

One wonders where the next discovery will take us in the quest to understand who we are and where we come from. We may have found our place in nature, located our twig on the shrub, but we are still searching for ourselves. We're only human, after all. SA

Kate Wong is a senior editor at *Scientific American.* She covers evolution and ecology.

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ARE WE WIRED DIFFERENTLY?

Parts of the brain involved in language and cognition have enlarged greatly over an evolutionary timescale

By Chet C. Sherwood

Graphics by Mesa Schumacher

Chet C. Sherwood is a professor of anthropology at the George Washington University. His work focuses on brain evolution in primates and other mammals.

Mesa Schumacher is a medical illustrator and science artist with a passion for clear communication and engaging visuals. She is the principal artist of Mesa Studios. Her work can be found in magazines, books, journals, museums, zoos, aquariums and educational games.

HUMANS ARE OFF THE SCALE. MODERN HUMAN BRAINS ARE ABOUT THREEFOLD LARGER than those of our earliest hominin ancestors and living great ape relatives. Across animals, brain size is tightly correlated with body size. But humans are the extreme outlier when gauged against this typical scaling relation. The average adult human brain is roughly three pounds, which is approximately 2 percent of body size. But it consumes an outsized 20 percent of the body's energy budget because of high levels of electrical activity by neurons and the metabolic fuel it takes to transmit chemical signals from one brain cell to the next.

Detailed comparisons of human brains with those of our close living primate relatives, including chimpanzees, have shown that the parts of the cerebral cortex involved in higher-order cognitive functions, such as creativity and abstract thinking, have become especially enlarged. These cortical areas, known as association regions, mature relatively late in postnatal development. Some of the long-range neural connections that link these association areas to one another and to the cerebellum (the latter plays a role in voluntary movement and learning new skills) are more numerous in human brains compared with other primates. These human-enhanced networks are loci for language, toolmaking and imitation. Even ancient reward systems in a subcortical area called the striatum, a hub of activity for the brain-signaling molecule dopamine, appear to have been reshaped in human brain evolution. That change most likely increases attention to social signals and facilitates language learning.

Where did our big brains come from? The hominin fossil record points to a general trend toward increased cranial capacity during the past six million years or so. That is when our lineage split from the last common ancestor we shared with chimpanzees and bonobos. Scientists consider a constellation of interrelated features of human biology to be associated with our large brains—slower growth through the stages of childhood, a longer life span, and more involvement in raising offspring by fathers and grandparents to assist mothers. Extended brain growth after birth means that significant events that lay the groundwork for cognition take place in a rich social and ecological context.

Another clue to what makes us different from chimpanzees and other intelligent species comes from compelling research that has uncovered genetic and molecular changes that occurred during the long course of the brain's evolution. A look at some of the distinctive features of the human brain follows.

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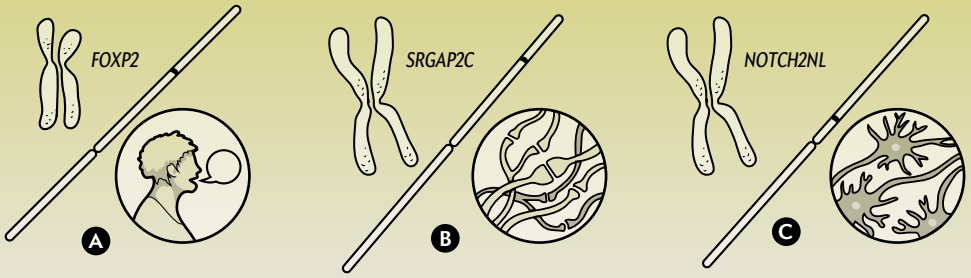
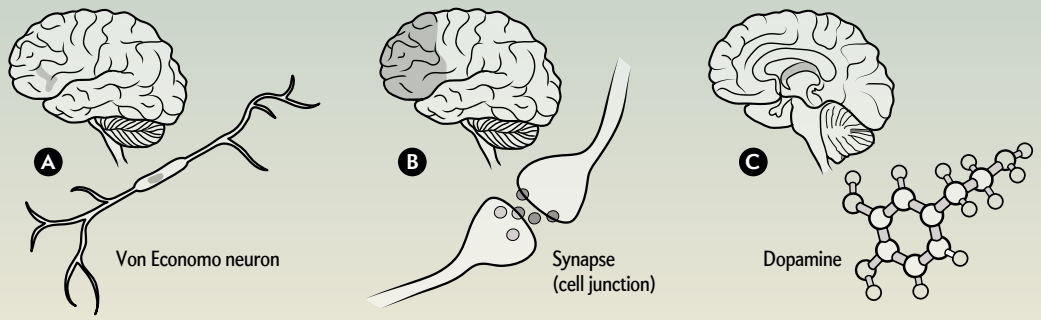


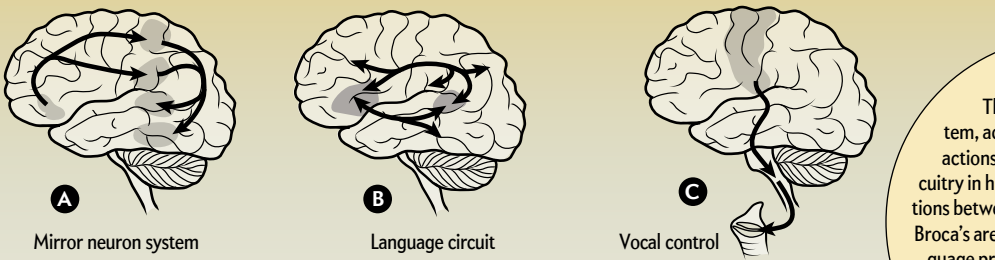
GENES

The variant of the *FOXP2* gene found in humans plays a role in vocal learning **A**. *SRGAP2C*, a unique duplicate of *SRGAP2* that is found only in humans, increases the density of neural connections **B**. A human version of a gene called *NOTCH*, known as *NOTCH2NL*, has three copies and aids in the production of neurons **C**.



CELLS

Von Economo neurons, which are pivotal in social-emotional brain circuits, are bigger in humans **A**. RNA that carries messages to instruct cells to make proteins is more active in the synapses of the prefrontal cortex (*dark area*) than it is in other primates **B**. Cells produce more of the neurotransmitter dopamine in the striatum. Dopamine is involved in various cognitive functions **C**.

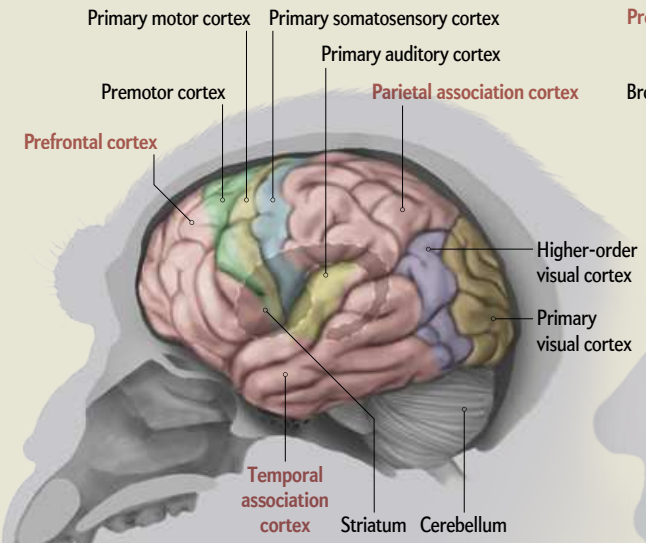


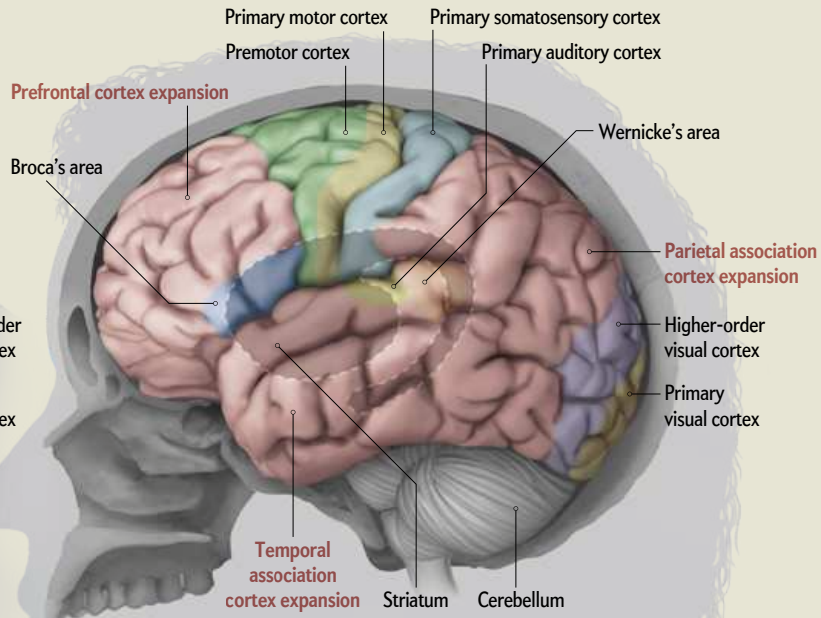
CIRCUITS

The mirror neuron system, activated when viewing the actions of others, has intricate circuitry in humans **A**. Expanded connections between two sites—Wernicke's and Broca's areas—form a vital circuit for language processing **B**. A link from the motor cortex to the brain stem coordinates the larynx muscles, a circuit absent in chimpanzees and macaques **C**.

REGIONAL EXPANSION

Brain areas responsible for higher cognitive functions grew disproportionately in humans compared with the same regions in chimpanzees—among them, the prefrontal, temporal association and parietal association cortices.





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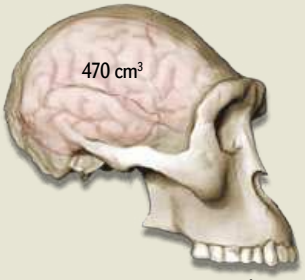
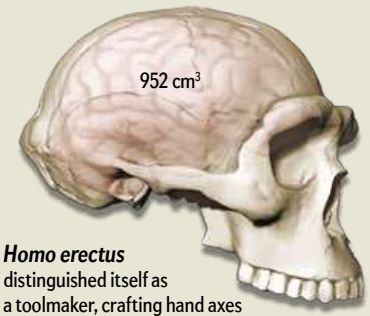
BIG BRAINS GOT US HERE

The last common ancestor that humans shared with chimpanzees and bonobos lived from six million to eight million years ago. After the two lines split, a number of evolutionary adaptations occurred: bipedalism, stone toolmaking and, notably, an increase in brain size in certain hominin species—a process that gained momentum as time passed.



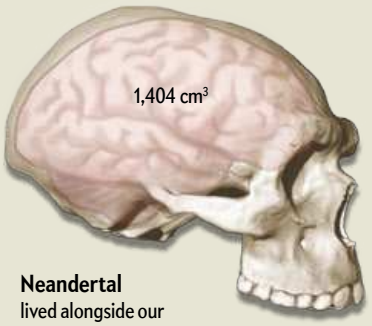
Australopithecus africanus
combined human and ape features. Its brain volume of 470 cubic centimeters (cm^3) was akin to that of chimpanzees.

3.3–2.1 million years ago (mya)



Homo erectus
distinguished itself as a toolmaker, crafting hand axes and expanding its home environment outside of Africa.

1.9 mya–143,000 years ago (143 kya)

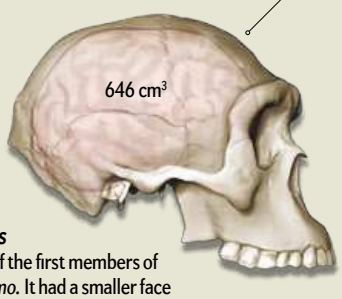


Neandertal
lived alongside our species and was an avid hunter and tool and fire user. Its braincase, at 1,404 cm^3, was comparable in volume to our own.

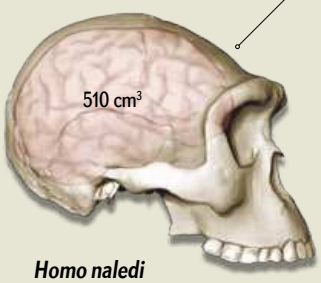
400–40 kya

335–236 kya

2.1–1.6 mya

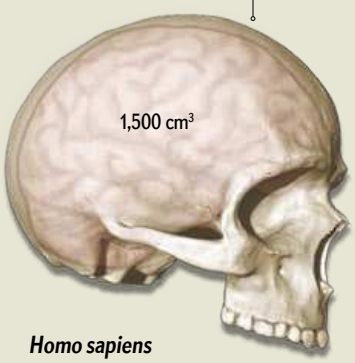


Homo habilis
became one of the first members of the genus *Homo*. It had a smaller face than its ancestors and developed frontal areas linked to language.



Homo naledi
was a newer member of the human lineage whose story demonstrates that evolution does not always move in straight lines. Its smaller braincase was 510 cm^3.

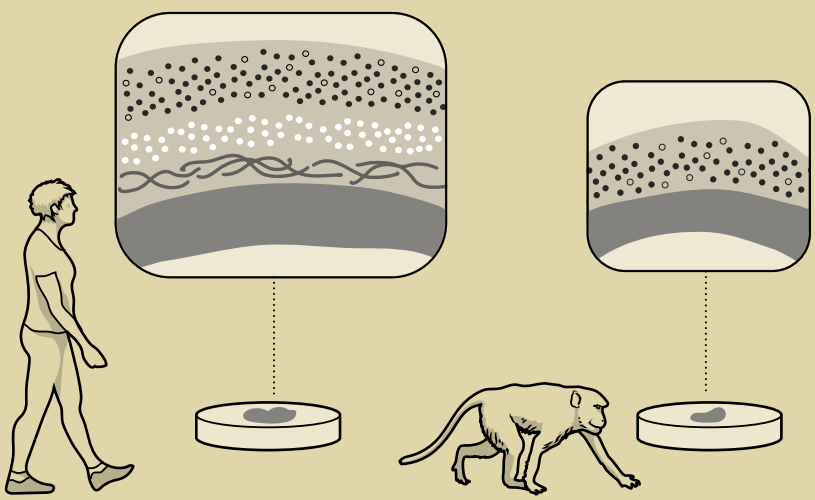
300 kya–present



Homo sapiens
evolved some 300,000 years ago. Our brain shape is spherical, or globular, because of the rounded shape of the parietal area and the cerebellum.

MINI BRAINS

Supplying nutrients to groups of stem cells in a lab dish allows them to grow into mini brains. These cerebral organoids, as they are called, consist of entire brain regions, such as the cortex of a human or a monkey (*cross-sectional views*). These ingenious research tools afford an opportunity to compare the activity of genes and neural circuit development in organoids with the working of actual brains in humans, nonhuman primates and other species, ultimately providing a clearer picture of what makes us unique.



HOW OUR BRAINS GROW

Compared with other primates, human babies have brains that are underdeveloped, grow more rapidly in the first year after birth, and then level off years later with a volume about three times larger than that of a chimpanzee.

Sources: "Developmental Patterns of Chimpanzee Cerebral Tissues Provide Important Clues for Understanding the Remarkable Enlargement of the Human Brain," by T. Sakai et al., in *Proceedings of the Royal Society B,* Vol. 270; February 22, 2013 (*brain area expansion*); "Mammalian Brains Are Made of These: A Dataset of the Numbers and Densities of Neuronal and Nonneuronal Cells in the Brain of Glires, Primates, Scandentia, Eulipotyphlans, Afrotherians and Artiodactyls, and Their Relationship with Body Mass," by S. Herculano-Houzel et al., in *Brain, Behavior and Evolution,* Vol. 86, Nos. 3–4; December 2015 (*human* and *macaque neuron numbers*); "Dogs Have the Most Neurons, though Not the Largest Brain: Trade-off between Body Mass and Number of Neurons in the Cerebral Cortex of Large Carnivoran Species," by D. Jardim-Messeder et al., in *Frontiers in Neuroanatomy,* Vol. 11, Article No. 118; December 2017 (*cat neuron number*); "Quantitative Relationships in Delphinid Neocortex," by H. S. Mortensen et al., in *Frontiers in Neuroanatomy,* Vol. 8, Article No. 132; November 2014 (*pilot whale neuron number*); "Cortical Cell and Neuron Density Estimates in One Chimpanzee Hemisphere," by C. E. Collins et al., in *PNAS,* Vol. 113, No. 3; January 19, 2016 (*chimpanzee neuron number*); "Human Evolutionary History," by E. K. Boyle and B. Wood, in *Evolution of Nervous Systems.* Second edition. Edited by J. H. Kaas. Academic Press, 2017 (*hominin evolution*); Smithsonian National Museum of Natural History *http://humanorigins.si.edu* (*hominin species time line*)

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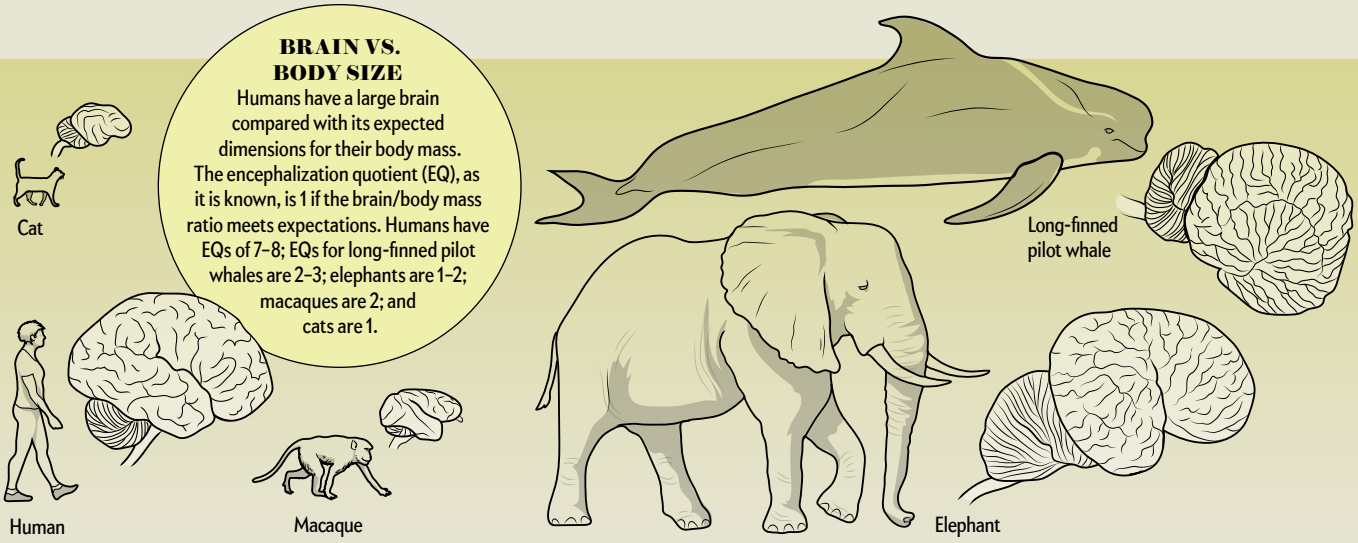
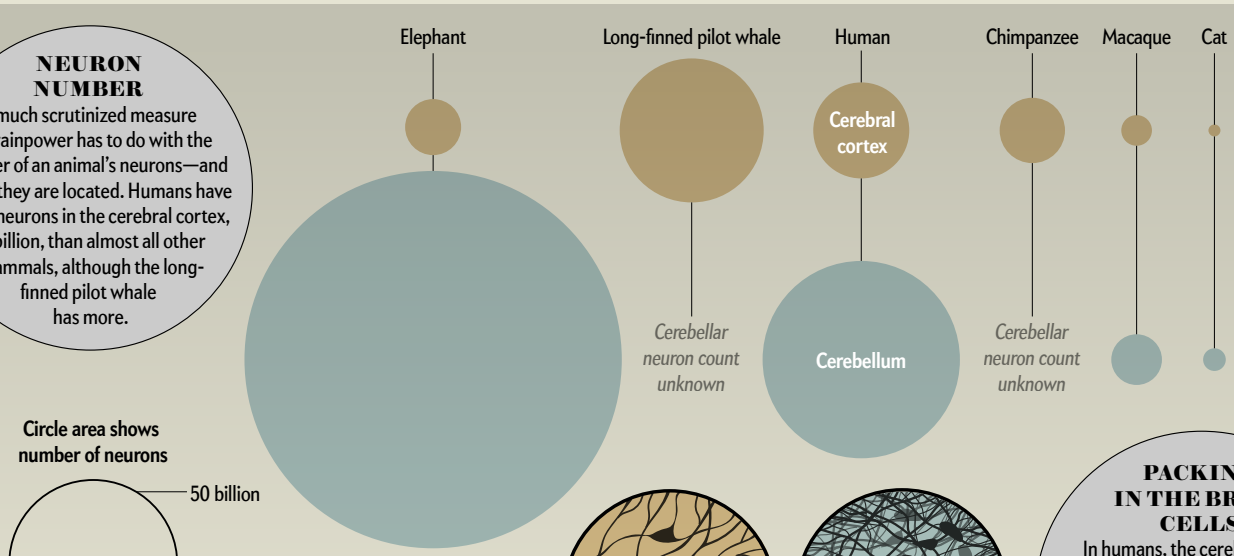
BRAIN VS. BODY SIZE

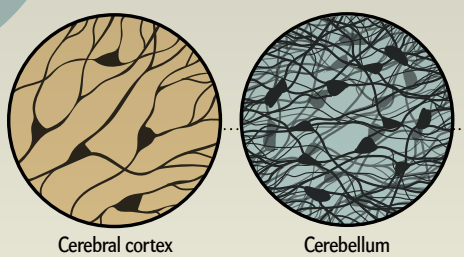
Humans have a large brain compared with its expected dimensions for their body mass. The encephalization quotient (EQ), as it is known, is 1 if the brain/body mass ratio meets expectations. Humans have EQs of 7–8; EQs for long-finned pilot whales are 2–3; elephants are 1–2; macaques are 2; and cats are 1.



NEURON NUMBER

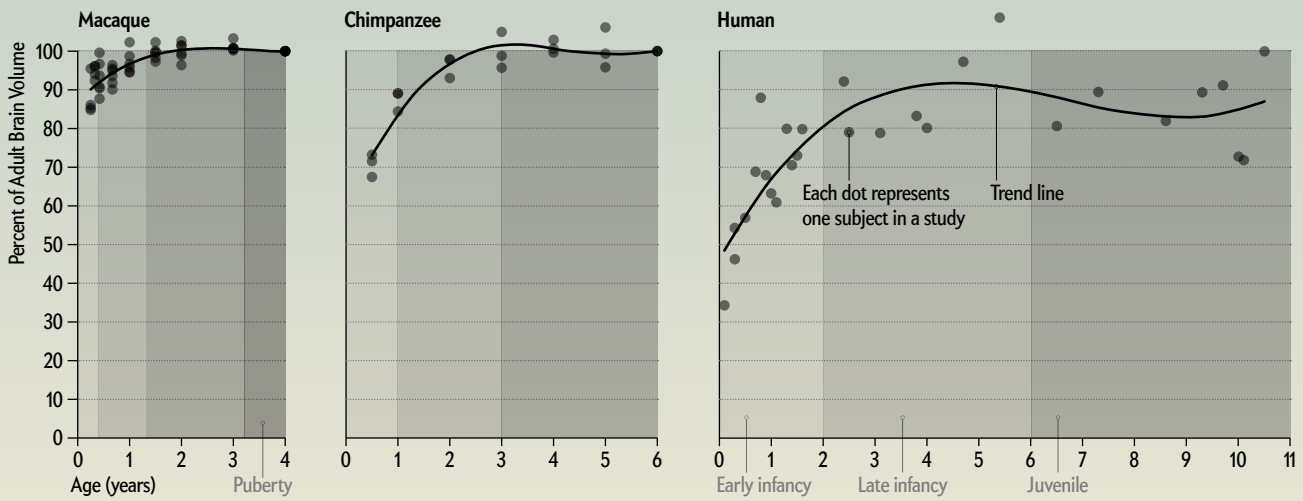
A much scrutinized measure of brainpower has to do with the number of an animal's neurons—and where they are located. Humans have more neurons in the cerebral cortex, 16 billion, than almost all other mammals, although the long-finned pilot whale has more.





PACKING IN THE BRAIN CELLS

In humans, the cerebral cortex makes up 82 percent of the brain's mass but contains only 19 percent of the total neurons, whereas the cerebellum holds 80 percent or so of the neurons but occupies only 10 percent of its mass.



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Survival of the Friendliest

Natural selection for hypersocial traits enabled Earth's apex species to best Neandertals and other competitors

By Brian Hare and Vanessa Woods

Illustrations by Matt Harrison Clough

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WE ARE THE ONLY HUMANS, BUT NOT SO LONG AGO WE had company. In the roughly 300,000 years of our existence, *Homo sapiens* has shared the planet with at least four other human species. In hindsight, it seems obvious why we prevailed. We were the best hunters, the smartest, the most technologically savvy.

But that is only the story we tell ourselves. Some of the other human species were more technologically advanced, had been around for much longer—a million years—or had brains as big as or bigger than ours. Going back 100,000 years ago, if you were to guess which human species was going to make it, one of the other humans, perhaps Neandertals, would have been a good bet.

We shared a common ancestor with Neandertals. They were stronger than us, barrel-chested with muscle. They were highly skilled with weapons and hunted every large mammal in the Ice Age. They even shared with us a variant of a gene known as *FOXP2,* thought to be required for the finely calibrated movements needed for speech. Their culture demonstrated high levels of sophistication: Neandertals buried their dead, cared for the sick and injured, painted themselves with pigment, and adorned themselves with jewelry made of shells, feathers and bone.

The first *H. sapiens* to arrive in Europe met a relatively large population of Neandertals who were well adapted to a cold climate. Later, as glaciers advanced, modern humans fled, and Neandertals stayed and thrived. Compared with our closest living relatives, bonobos and chimpanzees, our species has little genetic variation, which suggests that at some time, perhaps several times, we experienced a severe population bottleneck, which means we might almost have gone extinct.

If we were not the strongest or the smartest, how did we win?

HUMAN SELF-DOMESTICATORS

COMPARED WITH OTHER HUMAN SPECIES, it turns out we were the friendliest. What allowed us to thrive was a kind of cognitive superpower: a particular type of affability called cooperative communication. We are experts at working together with other people, even strangers. We can communicate with someone we have never met about a shared goal and work together to accomplish it. We develop this superpower before we can walk or talk, and it is the gateway to a sophisticated social and cultural world. It allows us to plug our minds into the minds of others and inherit the knowledge of generations. It is the foundation for all forms of culture and learning, including sophisticated language.

This friendliness evolved through self-domestication. Domestication is a process that involves intense selection for friendliness. When an animal is domesticated, in addition to becoming much friendlier, it undergoes many changes that appear completely unrelated to one another. This domestica-

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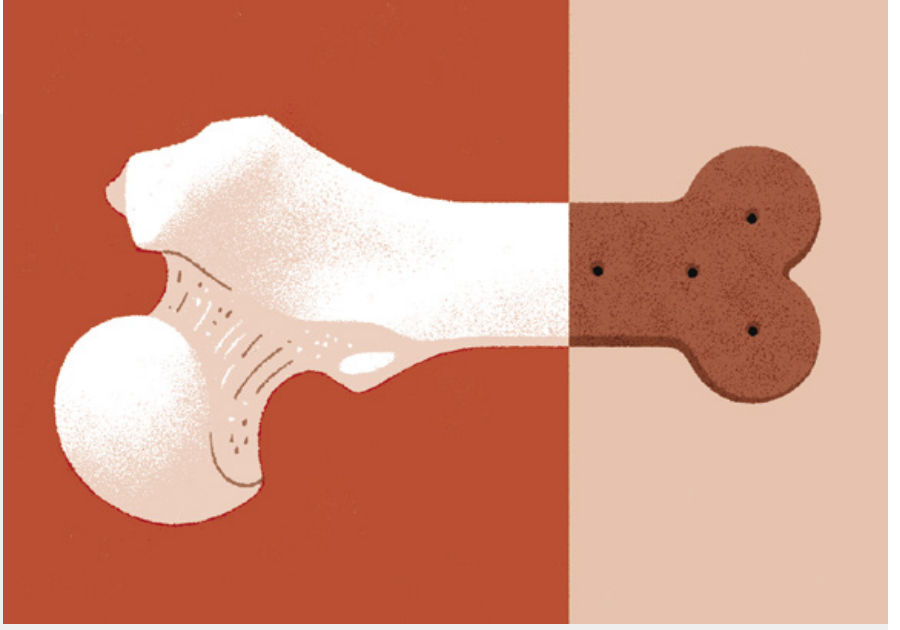
From Wolf to Dog

An amicable disposition also governed the course of evolution for an animal that turned into a favorite pet



Humans are not the only ones who underwent self-domestication. So did our close relatives, the bonobos, and the species we call our best friend. A tiny fraction of the genome differentiates dogs from wolves, and yet millions of dogs are snugly curled up in our homes, while wolves slink around at the edge of extinction. True, dogs run into doors and drink out of our toilets, but they also protect our loved ones, fight our wars, detect drugs and cancer, calm children with autism, and give many of us unconditional love and a reason to go outside and exercise.

When our research group began its work almost 20 years ago, we discovered that dogs also have extraordinary intelligence: they can read our gestures better than any other species, even bonobos and chimpanzees. Wolves, in contrast, are mysterious and unpredictable. Their home is the wilderness, and that wilderness is shrinking.

But not so long ago the evolutionary race between dogs and wolves was so close, it was unclear who would win. Dogs, in fact, did not descend from wolves. Instead dogs and wolves shared a wolflike ancestor, whom we will call Ice Age wolves to distinguish them from today's animals. These wolves were highly successful: they survived after every large carnivore—saber-toothed cats, cave lions and giant hyenas—had gone extinct. They spread throughout most of the Northern Hemisphere and became one of the most successful predators in the world.

Folklore supposes that humans brought wolf puppies into camp and domesticated them. Or as wolf expert David Mech wrote in 1974, "Evidently early humans tamed wolves and domesticated them, eventually selectively breeding them and finally developing the domestic dog (*Canis familiaris*) from them."

But this story has not held up. Taming an animal occurs during its lifetime. Domestication happens over generations and involves changes to the genome. That is only one difference between domesticating and taming an animal. Even today wolves eat too much meat—as much as 20 pounds in a single feeding—to be a sustainable hunting partner. Ice Age wolves were much larger than modern wolves. At the time of dog domestication, humans were hunter-gatherers, going out to forage and leaving their children in camp—no sensible human would have let them be unprotected against a carnivore of that size.

Dogs have shorter snouts and reduced versions of the long canine teeth compared with wolves. Their hair changes color to cover them in random splotches. Their tails curl, sometimes in a full circle—and they have floppy ears. Instead of having one breeding season, they can breed throughout the year.

Taken together, these traits are part of the domestication syndrome, and an assortment of them appear in a domesticated species. But no one knew what tied these traits together, or if they were related at all, until a Russian geneticist decided to domesticate foxes in a remote outpost in Siberia.

In 1959 Dmitry Belyaev began breeding them using a single selection criterion—whether the fox would approach a human hand. After 50 generations, these friendly foxes would leap into your arms, lick your face and pee for joy.

When our research group tested the foxes, we found that, like dogs, they were better at reading intentions from our gestures. The foxes were only bred to be unafraid and attracted to humans. But other changes, including an increase in social intelligence, happened by accident.

So how did wolves turn into dogs? Back in the Ice Age, as our human populations grew more sedentary, we probably created more trash, which we then dumped outside our camps. These leavings would have included tempting morsels for hungry wolves. Only the friendliest wolves would have been able to scavenge, however. These animals would have had to be unafraid of humans, and if they displayed any aggression toward us, they would have been killed.

These friendly wolves would have been at a reproductive advantage and, because they scavenged together, more likely to breed together. After generations of selection for friendliness without intentional selection by humans, this special population of wolves would have begun to take on a different appearance. Coat color, ears, tails: all probably started to change. We would have become increasingly tolerant of these odd-looking scavenger wolves and would quickly have discovered that they had a unique capacity for reading our gestures.

Animals that could respond to our gestures and voices would be extremely useful as hunting partners and guards. They would have been valuable as well for their warmth and companionship, and slowly we would have allowed them to move from outside our camps to our firesides. We did not domesticate dogs. The friendliest wolves domesticated themselves.

In the 14,000 to 40,000 years during which this domestication process occurred, wild wolves were probably doing better than dogs in terms of numbers—after all, our dogs were probably another food source for humans when times became lean. The first written record of a wolf hunt was recorded in the sixth century B.C.E., when Solon of Athens offered a bounty for every wolf killed.

This event was the start of a systematic massacre that almost eradicated wolves permanently. In 2003 the estimate of their population was 300,000 worldwide. A 2013 estimate of the population of dogs worldwide totals a billion. The history of dogs and wolves demonstrates how friendliness as a trait translates into a winning evolutionary strategy.

—B.H. and V.W.

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tion syndrome shows up in the shape of the face, the size of the teeth and the pigmentation of different body parts or hair; it includes changes to hormones, reproductive cycles and the nervous system. Although we think of domestication as something that we do to animals, it can also occur through natural selection, a process known as self-domestication.

The self-domestication hypothesis was developed over the past 20 or so years from our work with anthropologist Richard Wrangham of Harvard University and psychologist Michael Tomasello of Duke University. What we discovered through our research is that self-domestication also increases the key to our success—the ability to cooperatively communicate with others. The hypothesis predicts that if *H. sapiens* were self-domesticated, we should find evidence of selection for friendliness in the Pleistocene (2.6 million to 11,700 years ago). Although behavior does not fossilize, the neurohormones that regulate behavior shape our skeletons, and we can trace these changes through paleoanthropological specimens.

For example, the more testosterone you have available during puberty, the thicker your brow ridge and the longer your face becomes. Men tend to have thicker, more overhanging brow ridges and slightly longer faces than women, so we call a face with these traits masculinized. Testosterone does not directly cause human aggression, but its levels and its interactions with other hormones do modulate aggressive behavior.

Anthropologists have frequently remarked on the decreasing brow ridges, shortening faces and shrinking heads of humans throughout the Paleolithic. In our own research, we realized that if we documented those changes, they would point to when physiological changes occurred that shaped our behavior and our bodies at the same time.

Self-domestication is a scientific hypothesis that suggests *Homo sapiens* underwent selection for friendliness—as evidenced by both our behaviors and physical traits.

Together with researchers Steven Churchill and Robert Cieri, then both at Duke, we found that *H. sapiens* prior to the 80,000-year mark, the Middle Pleistocene, had longer faces and much larger brow ridges than in the Late Pleistocene. On average, skulls more recent than 80,000 years ago had a 40 percent reduction in how far their brow ridges projected from the face. They were also 10 percent shorter and 5 percent narrower than the older skulls before that dividing point. Although the pattern varied, it continued so that the faces of modern hunter-gatherers and agriculturalists grew more delicate in appearance, indicating a decrease in testosterone. Another neurohormone, serotonin, may have promoted a set of changes that led to smaller brains and less aggression. Increases in serotonin appear early on during the domestication syndrome—and the chemical may also be involved in skull development.

Drugs that increase serotonin availability in the brain, such as selective serotonin reuptake inhibitors (SSRIs), make people more cooperative and less willing to harm others when tested during social science experiments examining moral dilemmas and cooperation. Serotonin does not just change behavior. If exposure occurs early in development, it also appears to alter skull morphology. Pregnant mice given SSRIs have babies with shorter, narrower snouts and skulls described as globular.

Every other human species had a low, flat forehead and a thick skull. Neandertals had heads shaped like footballs. Only we have the balloonlike skulls that anthropologists call globular. This shape indicates a possible increase in the availability of serotonin during our evolutionary development. Based on the fossil record, these changes started after we split from our common ancestor with Neandertals—and they have continued in the relatively recent evolutionary past. In fact, the work of one of us (Hare) with Churchill and Cieri suggests that our skulls—and hence brain size—have been shrinking over the past 20,000 years.

If testosterone and serotonin levels changed in *H. sapiens* as a result of domestication, another molecule probably did as well. Lower testosterone and higher serotonin enhance the effects of the hormone oxytocin on social bonding. Oxytocin floods through mothers during childbirth. It facilitates milk production and is passed on through breast milk. Eye contact between parents and babies creates an oxytocin interactive loop, making both parent and baby feel loving and loved. When psychologist Carsten de Dreu of Leiden University in the Netherlands and other researchers gave people oxytocin to inhale in an experiment, the subjects tended to be more cooperative, empathetic and trusting in financial and social games.

All these changes had lasting impacts on our social relationships. In fact, we think these changes produced a new social category: the intragroup stranger. Our evolutionary cousins bonobos and chimpanzees recognize strangers based only on familiarity. Someone who lives with them inside their territory is a group member. Everyone else is a stranger. Recognition is clear-cut. An individual is either familiar or an outsider.

Chimpanzees may hear or see their neighbors, but the interaction is almost always brief and hostile; in contrast, bonobos are friendlier with outsiders. We, too, respond to individuals who are unfamiliar in different ways, but unlike any other animal, we also have the ability to instantly recognize whether a stranger belongs to our group. Only humans can define our groups based on appearance, language or a set of beliefs. Our ever changing conception of group status allows us to recognize those like us—even if we have never met them. It also lets us expand our social network far beyond the size of that of any other human species.

Every day, without thinking about it, we adorn ourselves in ways that make us identifiable to one another—donning sports

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jerseys, political pins or religious symbols on necklaces. This capacity dominates our modern lives. It encourages us to perform acts of kindness both great and small—donating an organ to a stranger or helping someone cross the street. It also helps us share and improve our best ideas.

THE LIGHTS STAY ON

EVEN THOUGH OUR NEANDERTAL COUSINS seemed to have an edge on us early on, around 80,000 years ago, signs that *H. sapiens* might not just prevail but flourish began to appear.

Glimpses of social sophistication and advanced technology can be found in archaeological remains from when we first emerged as a species in Africa as long as 300,000 years ago. But these sites were like lights blinking on and off. Technology and other signs of progress appeared, then disappeared. After 80,000 years ago these lights seemed to stay on and grow stronger. We think the new category of intragroup stranger appeared in our species around this time, when the fossil record suggests complex cultural traditions and technologies started to spread across long distances. Expanded social networks meant more cultural innovations could be shared at greater speed. Cultural and technological progress exploded.

From 50,000 years onward we began to leave evidence of our expanding social networks and cultural prowess wherever humans lived around the world. Jewelry made from shells has been found hundreds of miles inland, implying that an object with no practical value either was worth carrying some distance or was obtained from someone else who had traveled on one of our first trade routes. We painted animals on rocks so skillfully that the contours of the stone rippled beneath their bodies and seemingly gave them a third dimension.

The idea that friendliness led to our success is not new. Neither is the idea that as a species, we became more intelligent. Our discovery lies in the relationship between the two ideas: it was an increase in social tolerance that led to cognitive changes, especially those related to cooperative communication.

The arrival of human self-domestication would have led to both the increase in population and the revolution in technology we see in the fossil record. Friendliness drove these changes by linking groups of innovators together in a way other human species never could. Self-domestication gave us a superpower, and in the blink of an evolutionary eye, we took over the world. One by one, every other human species went extinct.

This optimistic view of our species is immediately at odds with the misery and suffering we still inflict on one another. If human self-domestication explains the best in us, does it also explain the worst? How do we reconcile our kindness with our cruelty?

Some of the same neurohormonal changes underlying friendliness also support horrific violence. Oxytocin seems crucial to parental behavior and has been called the hug hormone. But a better name would be the momma bear hormone. The same oxytocin that floods through a mother with the arrival of her newborn feeds the rage she feels when someone threatens that baby. For example, hamster mothers given extra oxytocin are more likely to attack and bite a threatening male. Oxytocin is also implicated in related forms of male aggression. Available oxytocin increases when a male rat bonds with his mate. He is more caring toward her but also more likely to attack a stranger threatening her. This link connecting social bonding, oxytocin and aggression is seen widely among mammals.

As our species was shaped by self-domestication, our increased friendliness also brought a new form of aggression. A higher availability of serotonin during human brain growth increased the impact of oxytocin on our behavior. Group members had the ability to connect with one another, and the bonds among them were so strong, they felt like family. New concern for others came with a willingness to violently defend unrelated group members. Humans became more violent when those we evolved to love more intensely were threatened.

LOVE IS A CONTACT SPORT

DESPITE THE EVOLUTIONARY PARADOXES of human nature, the perception of who belongs in our group is malleable. *H. sapiens* as a species has already demonstrated its capacity to expand the concept of group membership into the thousands and millions.

It can be extended further. The best way to diffuse conflict among groups is to diminish the perceived sense of threat through social interaction. If feeling threatened makes us want to protect others in our group, nonthreatening contact between groups allows us to expand the definition of who our group is.

White children who went to school with Black children in the 1960s were more likely, as they grew up, to support interracial marriage, have Black friends, and be willing to welcome Black people into their neighborhoods.

That formula still works in education. Pairs of roommates at the University of California, Los Angeles, who each were from a different race reported more comfort in mixed-race interactions and approval of mixed-race dating. One study found that imagining positive contact with one of the most dehumanized groups of people—the homeless—helps others to empathize with them. The friendships of individuals from different groups can also generalize beyond their friendship to other group members.

Most policies are enacted with the assumption that a change in attitude will lead to a change in behavior, but in the case of intergroup conflict, it is the altered behavior—in the form of human contact—that will most likely change minds. The self-domestication hypothesis explains why we as a species evolved to relate to others. Making contact between people of different ideologies, cultures or races is a universally effective reminder that we all belong to a single group called *H. sapiens*.

This gave us the edge we needed to outlast other members in the hominin line. In evolutionary terms, the definition of friendliness relates to positive behaviors, either intentional or unintentional, toward others. It involves not only close physical proximity while group size expanded but also an ability to rapidly read people's intentions. The benefits of social interactions on our species' success—the ability to solve problems better than individuals can on their own—proved so beneficial that it influenced the way selection shaped our bodies and minds. The resulting ability to share knowledge across generations produced the technology and culture that allowed us to populate every corner of the planet. SA

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New Limit on Longevity

Studies of blood cells and footsteps predict a new maximum human life span

By Emily Willingham

THE CHORUS OF THE THEME SONG FOR THE MOVIE *Fame,* performed by actress Irene Cara, includes the line "I'm gonna live forever." Cara was, of course, singing about the posthumous longevity that fame can confer. But a literal expression of this hubris resonates in some corners of the world—especially in the technology industry. In Silicon Valley, immortality is sometimes elevated to the status of a corporeal goal. Plenty of big names in big tech have sunk funding into ventures to solve the problem of death as if it were just an upgrade to your smartphone's operating system.

Yet what if death simply cannot be hacked and longevity will always have a ceiling, no matter what we do? Researchers have now taken on the question of how long we can live if, by some combination of serendipity and genetics, we do not die from cancer, heart disease or getting hit by a bus. They report that when omitting things that usually kill us, our body's capacity to restore equilibrium to its myriad structural and metabolic systems after disruptions still fades with time. And even if we make it through life with few stressors, this incremental decline sets the maximum life span for humans at somewhere between 120 and 150 years. In the end, if the obvious hazards do not take our lives, this fundamental loss of resilience will do so, the researchers conclude in findings published in May 2021 in *Nature Communications*.

"They are asking the question of 'What's the longest life that could be lived by a human complex system if everything else went really well, and it's in a stressor-free environment?'" says Heather Whitson, director of the Duke University Center for the Study of Aging and Human Development, who was not involved in the paper. The team's results point to an underlying "pace of aging" that sets the limits on life span, she says.

For the study, Timothy Pyrkov, a researcher at a Singapore-based company called Gero, and his colleagues looked at this "pace of aging" in three large cohorts in the U.S., the U.K. and Russia. To evaluate deviations from stable health, they assessed changes in blood cell counts and the daily number of steps taken and analyzed them by age groups.

For both blood cell and step counts, the pattern was the same: as age increased, some factor beyond disease drove a predictable and incremental decline in the body's ability to return blood cells or gait to a stable level after a disruption. When Pyrkov and his colleagues in Moscow and Buffalo, N.Y., used this predictable pace of decline to determine when resilience would disappear entirely, leading to death, they found a range of 120 to 150 years. (In 1997 Jeanne Calment, the oldest person on record to have ever lived, died in France at the age of 122.)

The researchers also found that with age, the body's response to insults could increasingly range far from a stable normal, requiring more time for recovery. Whitson says that this result makes sense: A healthy young person can produce a rapid physiological response to adjust to fluctuations and restore a personal

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JEANNE CALMENT enjoys her daily cigarette and glass of red wine on the occasion of her 117th birthday. In 1997 she died at the age of 122 and still holds the record for being the person with the longest life span.

Jean-Pierre Fizet *Getty Images*

norm. But in an older person, she says, "everything is just a little bit dampened, a little slower to respond, and you can get overshoots," such as when an illness brings on big swings in blood pressure.

Measurements such as blood pressure and blood cell counts have a known healthy range, however, Whitson points out, whereas step counts are highly personal. The fact that Pyrkov and his colleagues chose a variable that is so different from blood counts and still discovered the same decline over time may suggest a real pace-of-aging factor in play across different domains.

Study co-author Peter Fedichev, who trained as a physicist and co-founded Gero, says that although most biologists would view blood cell counts and step counts as "pretty different," the fact that both sources "paint exactly the same future" suggests that this pace-of-aging component is real.

The authors pointed to social factors that reflect the findings. "We observed a steep turn at about the age of 35 to 40 years that was quite surprising," Pyrkov says. For example, he notes, this period is often a time when an athlete's sports career ends, "an indication that something in physiology may really be changing at this age."

The desire to unlock the secrets of immortality has likely been around as long as humans' awareness of death. But a long life span is not the same as a long health span, says S. Jay Olshansky, a professor of epidemiology and biostatistics at the University of Illinois at Chicago, who was not involved in the work. "The focus shouldn't be on living longer but on living healthier longer," he says.

"Death is not the only thing that matters," Whitson says. "Other things, like quality of life, start mattering more and more as people experience the loss of them." The death modeled in this study, she says, "is the ultimate lingering death. And the question is: Can we extend life without also extending the proportion of time that people go through a frail state?"

The researchers' "final conclusion is interesting to see," Olshansky says. He characterizes it as "Hey, guess what? Treating diseases in the long run is not going to have the effect that you might want it to have. These fundamental biological processes of aging are going to continue."

The idea of slowing down the aging process has drawn attention, not just from Silicon Valley types who dream about uploading their memories to computers but also from a cadre of researchers who view such interventions as a means to "compress morbidity"—to diminish illness and infirmity at the end of life to extend health span. The question of whether this will have any impact on the fundamental upper limits identified in the *Nature Communications* paper remains highly speculative. But some studies are being launched—testing the diabetes drug metformin, for example—with the goal of attenuating hallmark indicators of aging.

In this same vein, Fedichev and his team are not discouraged by their estimates of maximum human life span. His view is that their research marks the beginning of a longer journey. "Measuring something is the first step before producing an intervention," Fedichev says. As he puts it, the next steps, now that the team has measured this independent pace of aging, will be to find ways to "intercept the loss of resilience." SA

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STILL EVOLVING

(After All These Years)

For 30,000 years our species has been changing remarkably quickly. And we're not done yet

By John Hawks

Illustration by Christian Northeast

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HUMANS ARE WILLFUL CREATURES. NO OTHER SPECIES ON THE PLANET HAS gained so much mastery over its own fate. We have neutralized countless threats that once killed us in the millions: we have learned to protect ourselves from the elements and predators in the wild; we have developed cures and treatments for many deadly diseases; we have transformed the small gardens of our agrarian ancestors into the vast fields of industrial agriculture; and we have dramatically increased our chances of bearing healthy children despite all the usual difficulties.

Many people argue that our technological advancement—our ability to defy and control nature—has made humans exempt from natural selection and that human evolution has effectively ceased. There is no "survival of the fittest," the argument goes, if just about everyone survives into old age. This notion is more than just a stray thought in the public consciousness. Professional scientists such as Steve Jones of University College London and respected science communicators such as David Attenborough have also declared that human evolution is over.

But it is not. We have evolved in our recent past, and we will continue to do so as long as we are around. If we take the more than seven million years since humans split from our last common ancestor with chimpanzees and convert it to a 24-hour day, the past 30,000 years would take about a mere six minutes. Yet much has unfolded during this last chapter of our evolution: vast migrations into new environments, dramatic changes in diet and a more than 1,000-fold increase in global population. All those new people added many unique mutations to the total population. The result was a pulse of rapid natural selection. Human evolution is not stopping. If anything, it is accelerating.

AN ANTHROPOLOGICAL LEGACY

SKELETONS OF ANCIENT PEOPLE have long suggested that humans evolved certain traits swiftly and recently. About 11,000 years ago, as people started to transition from hunting and gathering to farming and cooking, human anatomy changed. Ten thousand years ago, for example, people's teeth averaged more than 10 percent larger in Europe, Asia and North Africa than today. When our ancestors started to eat softer cooked foods that required less chewing, their teeth and jaws shrank, bit by bit, each generation.

Although anthropologists have known about such traits for decades, only in the past 15 years or so has it become clear just how new they really are. Studies of human genomes have made the recent targets of selection highly visible to us. It turns out, for example, that descendants of farmers are much more likely to have a greater production of salivary amylase, a key enzyme that breaks down starches in food. Most people alive today have several copies of the gene that codes for amylase, *AMY1*. Modern hunter-gatherers—such as the Datooga in Tanzania—tend to have far fewer copies than people whose ancestors came from farming populations, whether they live in Africa, Asia or the Americas. Getting a jump on starch processing at the point of entry seems to have been an advantage for ancient farmers wherever they adopted starchy grains.

Another dietary adaptation is one of the best-studied examples of recent human evolution: lactose tolerance. Nearly everyone in the world is born with the ability to produce the enzyme lactase, which breaks down the milk sugar lactose and makes it easier to extract energy from milk—essential for the survival of a suckling child. Most people lose this ability by adulthood. At least five different times in our recent evolutionary past, as people started to discover dairy, a genetic mutation arose to lengthen the activity of the lactase gene. Three of the mutations originated in different parts of sub-Saharan Africa, where there is a long history of cattle herding. Another one of the five genetic tweaks is common in Arabia and seems to have sprung up in ancient populations of camel and goat herders.

The fifth and most common variant of the mutation that keeps the lactase gene turned on in adulthood is found today in human populations stretching from Ireland to India, with its highest frequencies across northern Europe. The mutation originated in a single individual 7,500 years ago (give or take a few thousand years). In 2011 scientists analyzed DNA recovered from Ötzi the Iceman, who was naturally mummified about 5,500 years ago in northern Italy. He did not have the lactose-tolerance mutation, a hint that it had not yet become common in this region thousands of years after its initial origin. In following years, researchers sequenced DNA extracted from the skeletons of farmers who lived in Europe more than 5,000 years ago. None carried the lactase mutation. Yet in the same region today, the lactase-persistence mutation occurs in hundreds of millions of people—more than 75 percent of the gene pool. This is not a paradox but the mathematical expectation of natural selection. A new mutation under selection grows exponentially,

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taking many generations to become common enough to notice in a population. But once it becomes common, its continued growth is very rapid, and ultimately it dominates.

THE SHALLOWNESS OF RACES

WHAT IS PERHAPS MOST EXTRAORDINARY about our recent evolution is how many common physical features are completely new to human anatomy. The thick, straight black hair shared by most East Asians, for example, arose only within the past 30,000 years, thanks to a mutation in a gene called *EDAR,* which is crucial for orchestrating the early development of skin, hair, teeth and nails. That genetic variant traveled with early settlers of the Americas, all of whom share an evolutionary past with East Asians.

In fact, the overall evolutionary history of human skin, hair and eye pigmentation is surprisingly shallow. In the earliest stages of our evolution, all our ancestors had dark skin, hair and eyes. Since this initial state, dozens of genetic changes have lightened these features to some extent. A few of these changes are ancient variations present within Africa but more common elsewhere in the world. Most are new mutations that have emerged in one population or another: a change in a gene named *TYRP1,* for instance, that makes certain Solomon Islanders blond; the *HERC2* mutation that results in blue eyes; changes to *MC1R* that cause red hairs to sprout instead of black ones; and a mutation in the *SLC24A5* gene that lightens skin color and that is now found in up to 95 percent of Europeans. As in the case of lactase, ancient DNA is giving clear information about the antiquity of such mutations. Blue eyes seem to have appeared in people who lived more than 9,000 years ago, but the massive change to *SLC24A5* is not found in the DNA of ancient skeletons from the same time period. Skin, hair and eye color evolved with stunning speed.

Variations in pigmentation are some of the most obvious differences among people and, in some ways, the easiest to study. Scientists have also investigated much odder and less evident features of human anatomy. Consider the variations of earwax. Most people in the world today have sticky earwax. In contrast, many East Asians have dry, flaky earwax that does not stick together. Anthropologists have known about this variation for more than 100 years, but geneticists did not uncover the cause until recently. Dry earwax results from a relatively new mutation to a gene called *ABCC11.* Only 30,000 to 20,000 years old, the mutation also affects the apocrine glands, which produce sweat. If you have stinky armpits and sticky earwax, chances are you have the original version of *ABCC11.* If you have dry earwax and a little less need for deodorant, you probably have the newer mutation.

A few thousand years before dry earwax first appeared among East Asians, another seemingly simple mutation started saving millions of Africans from a deadly disease. A gene called *DARC* produces a starchy molecule on the surface of red blood cells that mops up excess immune system molecules known as chemokines from the blood. About 45,000 years ago a mutation in *DARC* conferred remarkable resistance to *Plasmodium vivax,* one of the two most prevalent malaria parasites infecting humans today. Parasites of this species enter red blood cells through the *DARC* molecule encoded by the gene, so

Recent Traits

Many commonplace features of human biology are relatively new. Blue eyes (*top*), straight, thick black hair (*bottom left*), the ability to digest milk in adulthood (*bottom right*) and some mutations that lightened skin all emerged in the past 30,000 years.

Anthony Lee *Getty Images (eye);* **Andreas Kuehn** *Getty Images (hair);* **daitoZen** *Getty Images (milk)*

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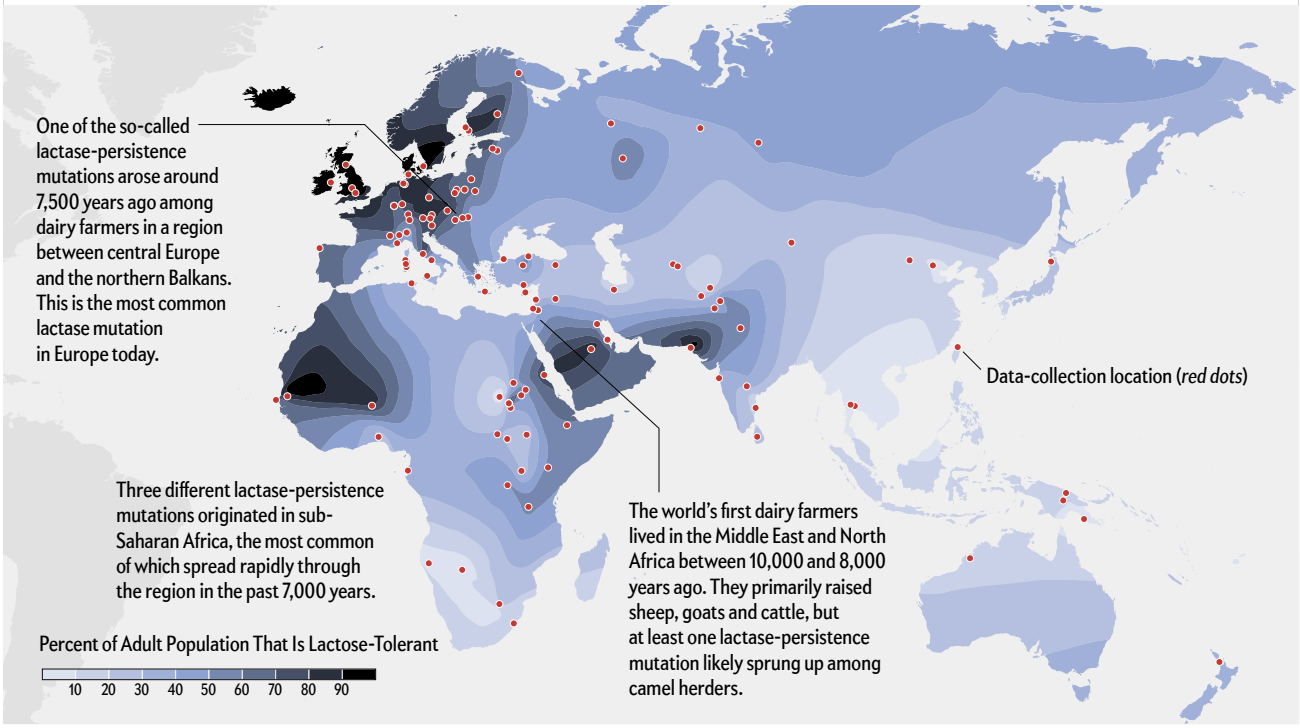
The Milk Mutation

Enjoying dairy in adulthood is a privilege that emerged relatively recently in our evolutionary history. We depend on the enzyme lactase to break down lactose, the sugar found in milk, but the human body usually stops producing lactase after adolescence. In fact, most of the world's adults are lactose-intolerant. Within the past 10,000 years, however, different populations of dairy farmers independently evolved genetic mutations that kept lactase active throughout life (lactase persistence). Scientists have identified several such mutations, but there are likely more. Collectively, all these adaptations explain the prevalence of lactose tolerance seen around the world today.


One of the so-called lactase-persistence mutations arose around 7,500 years ago among dairy farmers in a region between central Europe and the northern Balkans. This is the most common lactase mutation in Europe today.
Data-collection location (*red dots*)
Three different lactase-persistence mutations originated in sub-Saharan Africa, the most common of which spread rapidly through the region in the past 7,000 years.
The world's first dairy farmers lived in the Middle East and North Africa between 10,000 and 8,000 years ago. They primarily raised sheep, goats and cattle, but at least one lactase-persistence mutation likely sprung up among camel herders.
Percent of Adult Population That Is Lactose-Tolerant
10 20 30 40 50 60 70 80 90

hindering the expression of *DARC* keeps the pathogens at bay. The absence of *DARC* also increases the amount of inflammation-causing chemokines circulating in the blood, which has in turn been linked to an increase in prostate cancer rates in Black men. Yet on the whole, the mutation was so successful that 95 percent of people living south of the Sahara now have it, whereas only 5 percent of Europeans and Asians do.

THE POWER OF RANDOM

WE ARE ACCUSTOMED TO THINKING about evolution as a process of "good" genes replacing "bad" ones, but the most recent phase of human adaptation is a testament to the power of randomness in evolution. Beneficial mutations do not automatically persist. It all depends on timing and on population size.

I first learned this lesson from anthropologist Frank Livingstone. The beginning of my training coincided with the end of his long career, during which he investigated the genetic basis for malaria resistance. More than 3,000 years ago in Africa and India, a mutation arose in the gene encoding the oxygen-transporting blood cell molecule known as hemoglobin. When people inherited two copies of this mutation—dubbed hemoglobin S—they developed sickle cell anemia, a disease in which unusually shaped blood cells clog vessels. Red cells are normally supple and flexible enough to squeeze through tiny capillaries, but the mutant blood cells were rigid and deformed into the characteristic "sickle" shape. As it turns out, changing the shape of red blood cells also thwarted the ability of the malaria parasite to infect those cells.

Another mutation that interested Livingstone was hemoglobin E. Common in Southeast Asia today, hemoglobin E confers substantial malaria resistance without the severe side effects of hemoglobin S. "Hemoglobin E seems like it would be a lot better to have than hemoglobin S," I said in class one day. "Why didn't they get E in Africa?"

"It didn't happen there," Livingstone said.

His reply stunned me. I had supposed natural selection to be the most powerful force in evolution's arsenal. Humans had lived with deadly *Plasmodium falciparum* malaria for thousands of years in Africa.

Source: Global Lactase Persistence Association Database

Map by XNR Productions

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Surely natural selection would have weeded out less helpful mutations and hit on the most successful one.

Livingstone went on to show how the previous existence of hemoglobin S in a population made it harder for hemoglobin E to invade. Malaria rips through a population full of only normal hemoglobin carriers, and a new mutation that provides a slight advantage can quickly become more common. Yet a population already supplied with the protective hemoglobin S mutation will have a lower mortality risk. Sickle cell carriers still face formidable risks, but hemoglobin E is less of a *relative* advantage in a population that already has this imperfect form of malaria resistance. Perversely, what matters is not only the luck of having the mutation but also *when* the mutation happens. A partial adaptation that has bad side effects can win, at least over the few thousand years humans have been adapting to malaria.

Since humans first began battling malaria, scores of different genetic changes have emerged that increase immunity to the disease, different ones in different places. Each started as a serendipitous mutation that managed to persist in a local population despite being very rare at first. Any one of those mutations was, individually, unlikely to last long enough to become established, but the huge and rapidly increasing population size of our ancestors gave them many more rolls of the dice. As human populations have spread into new parts of the world and grown larger, they have rapidly adapted to their new homes precisely because those populations were so big.

OUR EVOLUTIONARY FUTURE

HUMAN POPULATIONS CONTINUE to evolve today. Unlike the distant past, where we must infer the action of selection from its long-term effects on genes, today scientists can watch human evolution in action, often by studying trends in health and reproduction. Even as medical technology, sanitation and vaccines have greatly extended life spans, birth rates in many populations still vacillate.

In sub-Saharan Africa, women who have a certain variant of a gene called *FLT1* and who are pregnant in the malarial season are slightly more likely to bear children than are pregnant women who lack the variant because the possessors have a lower risk that the placenta will be infected by malaria parasites. We do not yet understand how this gene reduces the risk of placental malaria, but the effect is profound and measurable.

Stephen Stearns of Yale University and his colleagues have examined years of records from long-term public health studies to see which traits may correlate with reproduction rates today. During the past 60 years, relatively short and heavy women in the U.S. who have low cholesterol counts had slightly more children on average than women who have the opposite traits. Why these traits have been related to family size is not yet clear.

Public health studies, such as U.K. Biobank, track the genotypes and lifetime health of hundreds of thousands of people. Such studies are being undertaken because the interactions of genes are complicated, and we need to examine thousands of outcomes to understand which genetic changes underlie human health. Tracing the ancestry of human mutations gives us tremendous power to observe evolution over hundreds of generations but can obscure the complex interactions of environment, survival and fertility that unfolded in the past. We see the long-term winners, such as lactase persistence, but may miss the short-term dynamics. Human populations are about to become the most intensively observed long-term experiment in evolutionary biology.

Instead of a mass of clones, we are already starting to see a glorious riot of variations—dark-skinned, freckled blondes and striking combinations of green eyes and olive skin.

What will the future of human evolution look like? Across the past few thousand years, human evolution has taken a distinctive path in different populations yet has maintained surprising commonality. New adaptive mutations may have elbowed their way into human populations, but they have not muscled out the old versions of genes. Instead the old, "ancestral" versions of genes mostly have remained with us. Meanwhile millions of people are moving between nations every year, leading to an unprecedented rate of genetic exchanges and mixture.

With such a high rate of genetic mixing, it may seem reasonable to expect that additive traits—for example, pigmentation, where many different genes have independent effects on skin color—will become ever more blended in future human populations. Could we be looking at a human future where we are a homogeneous soup instead of a colorful stew of variability?

The answer is no. Many of the traits that differ between human populations are not additive. Even pigmentation is hardly so simple, as is readily seen in mixed populations in the U.S., Mexico and Brazil. Instead of a mass of clones, we are already starting to see a glorious riot of variations—dark-skinned, freckled blondes and striking combinations of green eyes and olive skin. Each of our descendants will be a living mosaic of human history. SA

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MEASURING WHAT MATTERS

Obsession with one financial figure, GDP, has worsened people's health, happiness and the environment, and economists want to replace it

By Joseph E. Stiglitz

Illustrations by Samantha Mash

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SINCE WORLD WAR II, MOST COUNTRIES AROUND THE world have come to use gross domestic product, or GDP, as the core metric for prosperity. The GDP measures market output: the monetary value of all the goods and services produced in an economy during a given period, usually a year. Governments can fail if this number falls—and so, not surprisingly, governments strive to make it climb. But striving to grow GDP is not the same as ensuring the well-being of a society.

In truth, "GDP measures everything," as Senator Robert Kennedy famously said, "except that which makes life worthwhile." The number does not measure health, education, equality of opportunity, the state of the environment or many other indicators of the quality of life. It does not even measure crucial aspects of the economy such as its sustainability: whether or not it is headed for a crash. What we measure matters, though, because it guides what we do. Americans got an inkling of this causal connection during the Vietnam War, with the military's emphasis on "body counts": the weekly tabulation of the number of enemy soldiers killed. Reliance on this morbid metric led U.S. forces to undertake operations that had no purpose except to raise the body count. Like a drunk looking for his keys under the lamppost (because that is where the light is), the emphasis on body counts kept us from understanding the bigger picture: the slaughter was inducing more Vietnamese people to join the Viet Cong than U.S. forces were killing.

Now a different body count—that from COVID-19—is proving to be a horribly good measure of societal performance. It has little correlation with GDP. The U.S. is the richest country in the world, with a GDP of more than $20 trillion in 2019, a figure that suggested we had a highly efficient economic engine, a racing car that could outperform any other. But the U.S. has recorded more than 600,000 deaths, whereas Vietnam, with a GDP of $262 billion (and a mere 4 percent of U.S. GDP per capita), has had fewer than 500 to date. In the race to save lives, this less prosperous country has beaten us handily.

In fact, the American economy is more like an ordinary car whose owner saved on gas by removing the spare tire, which was fine until he got a flat. And what I call "GDP thinking"—seeking to boost GDP in the misplaced expectation that that alone would enhance well-being—led us to this predicament. An economy that uses its resources more efficiently in the short term has higher GDP in that quarter or year. Seeking to maximize that macroeconomic measure translates, at a microeconomic level, to each business cutting costs to achieve the highest possible short-term profits. But such a myopic focus necessarily compromises the performance of the economy and society in the long term.

The U.S. health care sector, for example, took pride in using hospital beds efficiently: no bed was left unused. In consequence, when SARS-CoV-2 reached America there were only 2.8 hospital beds per 1,000 people—far fewer than in other advanced countries—and the system could not absorb the sudden surge in patients. Doing without paid sick leave in meat-packing plants increased profits in the short run, which also increased GDP. But workers could not afford to stay home when sick; instead they came to work and spread the infection. Similarly, China made protective masks cheaper than the U.S. could, so importing them increased economic efficiency and GDP. That meant, however, that when the pandemic hit and China needed far more masks than usual, hospital staff in the U.S. could not get enough. In sum, the relentless drive to maximize short-term GDP worsened health care, caused financial and physical insecurity, and reduced economic sustainability and resilience, leaving Americans more vulnerable to shocks than the citizens of other countries.

The shallowness of GDP thinking had already become evident in the 2000s. In preceding decades, European economists, seeing the success of the U.S. in increasing GDP, had encouraged their leaders to follow American-style economic policies. But as signs of distress in the U.S. banking system mounted in 2007,

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France's President Nicolas Sarkozy realized that any politician who single-mindedly sought to push up GDP to the neglect of other indicators of the quality of life risked losing the confidence of the public. In January 2008 he asked me to chair an international commission on the Measurement of Economic Performance and Social Progress. A panel of experts was to answer the question: How can nations improve their metrics? Measuring that which makes life worthwhile, Sarkozy reasoned, was an essential first step toward enhancing it.

Coincidentally, our initial report in 2009, provocatively entitled *Mismeasuring Our Lives: Why GDP Doesn't Add Up,* was published right after the global financial crisis had demonstrated the necessity of revisiting the core tenets of economic orthodoxy. It met with such positive resonance that the Organization for Economic Co-operation and Development (OECD)—a think tank that serves 38 advanced countries—decided to follow up with an expert group. After six years of consultation and deliberation, we reinforced and amplified our earlier conclusion: GDP should be dethroned. In its place, each nation should select a "dashboard"—a limited set of metrics that would help steer it toward the future its citizens desired. In addition to GDP itself, as a measure for market activity (and no more) the dashboard would include metrics for health, sustainability and any other values that the people of a nation aspired to, as well as for inequality, insecurity and other harms that they sought to diminish.

These documents have helped crystallize a global movement toward improved measures of social and economic health. The OECD has adopted the approach in its Better Life Initiative, which recommends 11 indicators—and provides citizens with a way to weigh these for their own country, relative to others, to generate an index that measures their performance on the things they care about. The World Bank and the International Monetary Fund (IMF), traditionally strong advocates of GDP thinking, are now also paying attention to environment, inequality and sustainability of the economy.

A few countries have even incorporated this approach into their policy-making frameworks. New Zealand, for instance, embedded "well-being" indicators in the country's budgetary process in 2019. As the country's finance minister, Grant Robertson, put it: "Success is about making New Zealand both a great place to make a living and a great place to make a life." This emphasis on well-being may partly explain the nation's triumph over COVID-19, which appears to have been limited to roughly 3,000 cases and 26 deaths in a total population of nearly five million.

APPLES AND ARMAMENTS

NECESSITY IS THE MOTHER of invention. Just as the dashboard emerged from a dire need—the inadequacy of the GDP as an indicator of well-being, as revealed by the Great Recession of 2008—so did the GDP. During the Great Depression, U.S. officials could barely quantify the problem. The government did not collect statistics on either inflation or unemployment, which would have helped them steer the economy. So the Department of Commerce charged economist Simon Kuznets of the National Bureau of Economic Research with creating a set of national statistics on income. Kuznets went on to construct the GDP in the 1940s as a simple metric that could be calculated from the exceedingly limited market data then available. An aggregate of (the dollar value of) the goods and services produced in the country, it was equivalent to the sum of everyone's income—wages, profits, rents and taxes. For this and other work, he received the Nobel Memorial Prize in Economic Sciences in 1971. (Economist Richard Stone, who created similar statistical systems for the U.K., received the prize in 1984.)

Kuznets repeatedly warned, however, that the GDP only measured market activity and should not be mistaken for a metric of social or even economic well-being. The figure included many goods and services that were harmful (including, he believed, armaments) or useless (financial speculation) and excluded many essential ones that were free (such as caregiving by homemakers). A core difficulty with constructing such an aggregate is that there is no natural unit for adding the value of even apples and oranges, let alone of such disparate things as armaments, financial speculation and caregiving. Thus, economists use their prices as a proxy for value—in the belief that, in a competitive market, prices reflect how much people value apples, oranges, armaments, speculation or caregiving relative to one another.

> The relentless drive during the pandemic to maximize short-term GDP worsened health care and reduced economic resilience.

This profoundly problematic assumption—that price measures relative value—made the GDP quite easy to calculate. As the U.S. recovered from the Depression by ramping up the production and consumption of material goods (in particular, armaments during World War II), GDP grew rapidly. The World Bank and the IMF began to fund development programs in former colonies around the world, gauging their success almost exclusively in terms of GDP growth.

Over time, as economists focused on the intricacies of comparing GDP in different eras and across diverse countries and constructing complex economic models that predicted and explained changes in GDP, they lost sight of the metric's shaky foundations. Students seldom studied the assumptions that went into constructing the measure—and what these assumptions meant for the reliability of any inferences they made. Instead the objective of economic analysis became to explain the movements of this artificial entity. GDP became hegemonic across the globe: good economic policy was taken to be whatever increased GDP the most.

In 1980, following a period of seemingly poor economic performance—stagflation, marked by slow growth and rising prices—President Ronald Reagan assumed office on the promise of ramping up the economy. He deregulated the financial sector and cut taxes for the better-off, arguing that the benefits would "trickle

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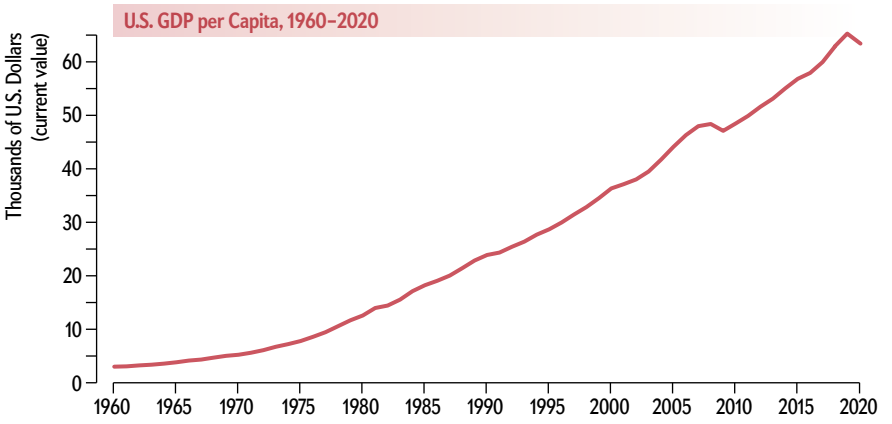
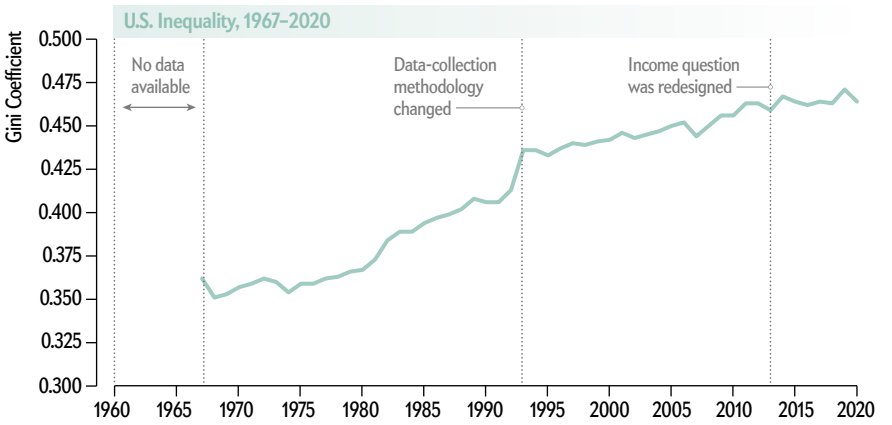
(Mis)measuring Well-Being

Gross domestic product, or GDP, measures the total quantity of goods and services produced in an economy in a certain period, usually a year. Though commonly used to indicate how well an economy and society are doing, it is merely a measure of market activity—no more. Since the Great Recession of 2008, a global movement has emerged to replace the GDP with a "dashboard" of indicators that can better help steer countries toward a healthier and more sustainable future.

FAIR SHARE

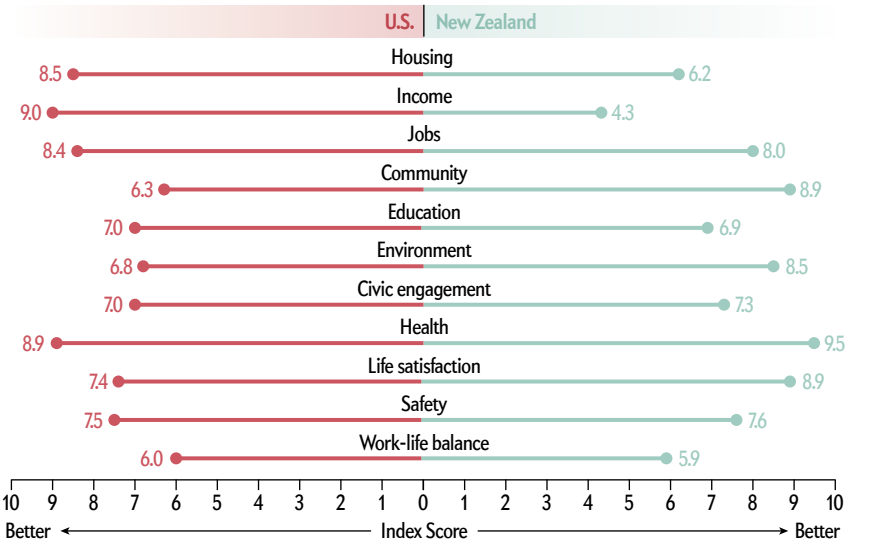
The GDP per capita is obtained by dividing the GDP by the population of a country and can increase even if the quality of life of most people in a country worsens. A key indicator of the divergence between GDP and social well-being is inequality. In the U.S., for instance, the GDP has increased steadily since the 1960s, but so has inequality. The three richest men in the U.S. already own more wealth than the bottom half of the population combined, and the pandemic is aggravating the disparity.





QUALITY OF LIFE

The Organization of Economic Co-operation and Development (OECD) lists 11 indicators for the quality of life. This chart compares the performances of two OECD members on these metrics. Although per capita income is far higher in the U.S., New Zealand scores better on the quality of environment and health, life satisfaction, and a sense of community and civic engagement.



Sources: World Bank (*GDP data*); U.S. Census Bureau (*inequality data*); Organization for Economic Co-operation and Development (*Better Life Index data*)

Graphic by Amanda Montañez

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down" to those less fortunate. Although GDP grew somewhat (albeit at a rate markedly lower than in the decades after World War II), inequality rose precipitously. Well aware that metrics matter, some members of the administration reportedly argued for stopping the collection of statistics on inequality. If Americans did not know how bad inequality was, presumably we would not worry about it.

The Reagan administration also unleashed unprecedented assaults on the environment, issuing leases for fossil-fuel extraction on millions of acres of public lands, for example. In 1995 I joined the Council of Economic Advisers for President Bill Clinton. Worrying that our metrics paid too little attention to resource depletion and environmental degradation, we worked with the Department of Commerce to develop a measure of "green" GDP, which would take such losses into account. When the congressional representatives from the coal states got wind of this, however, they threatened to cut off our funding unless we stopped our work, which we were obliged to.

The politicians knew that if Americans understood how bad coal was for our economy *correctly measured,* then they would seek the elimination of the hidden subsidies that the coal industry receives. They might even seek to move more quickly to renewables. Although our efforts to broaden our metrics were stymied, the fact that these representatives were willing to spend so much political capital on stopping us convinced me we were on to something important. (It also meant that when, a decade later, Sarkozy approached me about heading an international panel to examine better ways of measuring "economic performance and social progress," I leaped at the chance.)

I left the Council of Economic Advisers in 1997, and in the ensuing years the deregulatory fervor of the Reagan era came to grip the Clinton administration. The financial sector of the U.S. economy was ballooning, driving up GDP. As it turned out, many of the profits that gave that sector such heft were, in a sense, phony. Bankers' lending practices had generated a real-estate bubble that had artificially enhanced profits—and, with their pay being linked to profits, had increased their bonuses. In the ideal free-market economy, an increase in profits is supposed to reflect an increase in societal well-being, but the bankers' takings put the lie to that notion. Much of their profits resulted from making others *worse* off, such as when they engaged in abusive credit-card practices or manipulated LIBOR (for London Interbank Offered Rate of interest for international banks lending to one another) to enhance their earnings.

But GDP figures took these inflated figures at face value, convincing policy makers that the best way to grow the economy was to remove any remaining regulations that constrained the finance sector. Long-standing prohibitions on usury—charging outrageous interest rates to take advantage of the unwary—were stripped away. In 2000 the so-called Commodity Modernization Act was passed. It was designed to ensure that derivatives (risky financial products that played a big role in bringing down the financial system just eight years later) would never be regulated. In 2005 a bankruptcy law made it more difficult for those having trouble paying their bills to discharge their debts—making it almost impossible for those with student loans to do so.

By the early 2000s two fifths of corporate profits came from the financial sector. That fraction should have signaled that something was wrong: an efficient financial sector should entail low costs for engaging in financial transactions and therefore should be small. Ours was huge. Untethering the market had inflated profits, driving up GDP—and, as it turned out, instability.

OPIOIDS, HURRICANES

THE BUBBLE BURST in 2008. Banks had been issuing mortgages indiscriminately, on the assumption that real-estate prices would continue to rise. When the housing bubble broke, so did the economy, falling more than it had since the immediate aftermath of World War II. After the U.S. government rescued the banks (just one firm, AIG, received a government bailout of $130 billion), GDP improved, persuading President Barack Obama and the Federal Reserve to announce that we were well on the way to recovery. But with 91 percent of the gains in income in 2009 to 2012 going to the top 1 percent, the majority of Americans experienced none.

Metrics matter: some argued that if Americans did not know how bad inequality was, presumably we would not worry about it.

As the country slowly emerged from the financial crisis, others commanded attention: the inequality crisis, the climate crisis and an opioid crisis. Even as GDP continued to rise, life expectancy and other broader measures of health worsened. Food companies were developing and marketing, with great ingenuity, addictive sugar-rich foods, augmenting GDP but precipitating an epidemic of childhood diabetes. Addictive opioids led to an epidemic of drug deaths, but the profits of Purdue Pharma and the other villains in that drama added to GDP. Indeed, the medical expenditures resulting from these health crises also boosted GDP. Americans were spending twice as much per person on health care than the French but had lower life expectancy. So, too, coal mining seemingly boosted the economy, and although it helped to drive climate change, worsening the impact of hurricanes such as Harvey, the efforts to rebuild again added to GDP. The GDP number provided an optimistic gloss to the worst of events.

These examples illustrate the disjuncture between GDP and societal well-being and the many ways that GDP fails to be a good measure of economic performance. The growth in GDP before 2008 was not sustainable, and it was not sustained. The increase in bank profits that seemed to fuel GDP in the years before the crisis were not only at the expense of the well-being of the many people whom the financial sector exploited but also at the expense of GDP in later years. The increase in inequality was by any measure hurting our society, but GDP was celebrating the

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banks' successes. If there ever was an event that drove home the need for new ways of measuring economic performance and societal progress, the 2008 crisis was it.

THE DASHBOARD

THE COMMISSION, led by three economists (Amartya Sen of Harvard University, Jean-Paul Fitoussi of the Paris Institute of Political Studies and me), published its first report in 2009, just after the U.S. financial system imploded. We pointed out that measuring something as simple as the fraction of Americans who might have difficulty refinancing their mortgages would have illuminated the smoke and mirrors underpinning the heady economic growth preceding the crisis and possibly enabled policy makers to fend it off. More important, building and paying attention to a broad set of metrics for present-day well-being and its sustainability—whether good times are durable—would help buffer societies against future shocks.

We need to know whether, when GDP is going up, indebtedness is increasing or natural resources are being depleted; these may indicate that the economic growth is not sustainable. If pollution is rising along with GDP, growth is not environmentally sustainable. A good indicator of the true health of an economy is the health of its citizens, and if, as in the U.S., life expectancy has been going down—as it was even before the pandemic—that should be worrying, no matter what is happening to GDP. If median income (that of the families in the middle) is stagnating even as GDP rises, that means the fruits of economic growth are not being shared.

It would have been nice, of course, if we could have come up with a single measure that would summarize how well a society or even an economy is doing—a GDP plus number, say. But as with the GDP itself, too much valuable information is lost when we form an aggregate. Say, you are driving your car. You want to know how fast you are going and glance at the speedometer. It reads 70 miles an hour. And you want to know how far you can go without refilling your tank, which turns out to be 200 miles. Both those numbers are valuable, conveying information that could affect your behavior. But now assume you form a simple aggregate by adding up the two numbers, with or without "weights." What would a number like 270 tell you? Absolutely nothing. It would not tell you whether you are driving recklessly or how worried you should be about running out of fuel.

That was why we concluded that each nation needs a dashboard—a set of numbers that would convey essential diagnostics of its society and economy and help steer them. Policy makers and civil-society groups should pay attention not only to material wealth but also to health, education, leisure, environ-

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ment, equality, governance, political voice, social connectedness, physical and economic security, and other indicators of the quality of life. Just as important, societies must ensure that these "goods" are not bought at the expense of the future. To that end, they should focus on maintaining and augmenting, to the extent possible, their stocks of natural, human, social and physical capital. We also laid out a research agenda for exploring links between the different components of well-being and sustainability and developing good ways to measure them.

Concern about climate change and rising inequality had already been fueling a global demand for better measures, and our report crystallized that trend. In 2015 a contentious political process culminated in the United Nations establishing a set of 17 Sustainable Development Goals. Progress toward them is to be measured by 232 indicators, reflecting the manifold concerns of governments and civil societies from around the world. So many numbers are unhelpful, in our view: one can lose sight of the forest for the trees. Instead another group of experts, chaired by Fitoussi, Martine Durand (chief statistician of the OECD) and me, recommended that each country institute a robust democratic dialogue to discover what issues its citizens most care about.

Such a conversation would almost certainly show that most of us who live in highly developed economies care about our material well-being, our health, the environment around us and our relations with others. We want to do well today but also in the future. We care about how the fruits of our economy are shared: we do not want a society in which a few at the top grab everything for themselves and the rest live in poverty. A good indicator of the true health of an economy is the health of its citizens. A decline in life expectancy, even for a part of the population, should be worrying, whatever is happening to GDP. And it is important to know if, even as GDP is going up, so, too, is pollution—whether it is emissions of greenhouse gases or particulates in the air. That means growth is not environmentally sustainable.

The choice of indicators may vary across time and among countries. Countries with high unemployment will want to track what is happening to that variable; those with high inequality will want to monitor that. Still, because people generally want to know how they are doing in comparison with others, we recommended that the advanced countries, at least, share some five to 10 common indicators.

GDP would be among them. So would a measure of inequality or some pointer toward how the typical individual or household is doing. Over the years economists have formulated a rash of indicators of inequality, each reflecting a different dimension of the phenomenon. It may well be that societies where inequality has become particularly problematic may need to have metrics reflecting the depth of the poverty at the bottom and the excesses of riches at the top. To me, knowing what is happening to median income is of particular importance; in the U.S., median income has barely changed for decades, even as GDP has grown.

Employment is often used as an indicator of macroeconomic performance—an economy with a high unemployment rate clearly is not using all of its resources well. But in societies where paid work is associated with dignity, employment is a value in its own right. Other elements of the dashboard would include indicators for environmental degradation (say, air or water quality), economic sustainability (indebtedness), health (life expectancy) and insecurity.

Insecurity has both subjective and objective dimensions. We can survey how insecure people feel: how worried they are about adverse effects or how prepared they feel to cope with a shock. But we can also predict the likelihood that someone falls below the poverty line in any given year. And some elements of the dashboard are "intermediate" variables—things that we may (or may not) value in themselves but that provide an inkling of how a society will function in the future. One of these is trust. Societies in which citizens trust their governments and one another to "do the right thing" tend to perform better. In fact, societies in which people have higher levels of trust, such as Vietnam and New Zealand, have dealt far more effectively with the pandemic than the U.S., for instance, where trust levels have declined since the Reagan era. Policy makers need to use such indicators much as physicians use their diagnostic tools. When some indicator is flashing yellow or red, it is time to look deeper. If inequality is high or increasing, it is important to know more: What aspects of inequality are getting worse?

We want to do well today but also in the future. We care about how the fruits of our economy are shared.

STEERING THROUGH STORMS

SINCE WE BEGAN our work on well-being indicators some dozen years ago, I have been amazed at the resonance that it has achieved. A focus on many of the elements of the dashboard has permeated policy making everywhere. Every three years the OECD hosts an international conference of nongovernmental organizations, national statisticians, government officials and academics furthering the "well-being" agenda, the most recent being in Korea in November 2018, with thousands of participants.

Whenever the conference next convenes, the global crisis in human societies that a microscopic virus has precipitated will surely be on the agenda. The full dimensions of it could take years or decades to become clear. Recovering from this calamity and steering complex societies through the even more devastating crises that loom—catastrophic climate change and biodiversity collapse—will require, at the very least, an excellent navigational system. To paraphrase the OECD: We have been developing the tools to help us drive better. It is time to use them. SA

Joseph E. Stiglitz is a University Professor at Columbia University and chief economist at the Roosevelt Institute. He received the Nobel prize in economics in 2001. Stiglitz chaired President Bill Clinton's Council of Economic Advisers from 1995 to 1997 and served as the chief economist and senior vice president of the World Bank from 1997 to 2000. He chaired the Sarkozy commission (2008–2009) and an expert group (2013–2019) at the OECD for devising measures for well-being and sustainability.

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A TALE OF TWO WORLDS

Who will prosper, and who will fall behind?

By Mara Hvistendahl

LENA AND SAHEED HAVE NEVER MET; they probably never will. Lena lives in 2050 Leipzig, a placid and historic German city of middle-aged professionals. At 51, she is midway through a career as a pharmacist, with retirement more than two decades away. She and her husband no longer have to support their only child, a daughter who has graduated from college, but they worry about caring for their aging parents, who are in fairly good health in their 80s and 90s. Saheed, unattached and unemployed at 22, lives in a marginalized, low-income settlement on the outskirts of 2050 Lagos, Nigeria. He and his three siblings face a very different

Photograph by Andrew Myers

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kind of struggle: finding jobs in a tight labor market overrun with young workers, along with obtaining housing and clean water.

Lena worries about chronic diseases. Saheed is more likely to contract malaria. Germany scrambles to adapt its pension, health care and utility systems to a shrinking population that is living longer than ever before. Nigeria struggles to build roads, schools and sanitation facilities as its cities grow.

Lena's and Saheed's lives could hardly be more different. But these two divergent fictional figures embody many challenges that lie ahead. The distribution of the human population stands to change in unprecedented ways over the next few decades, forcing governments and the international community to rethink what it takes to protect the health and well-being of people around the globe. The decisions they make today will determine whether people like Lena and Saheed have a bright, or a bleak, future.

POPULATION MOMENTUM

ROUGHLY HALF A CENTURY AGO popular attention fixed on just one global population trend: sheer size. In his 1968 best seller *The Population Bomb,* Stanford University entomologist Paul R. Ehrlich warned that rapid population growth would outstrip production of food and other resources, with hundreds of millions dying of famine. Ehrlich's fears were not realized, however. The green revolution soon improved food security, and a mixture of economic development and access to education and family planning brought down birth rates in much of the world. By 1970 annual population growth had begun to decline from its 1960s peak of 2 percent.

And yet population growth is like a moving train—even as it slows, it possesses great momentum. Today the global growth rate continues to decline, but billions more will still be added to the human population over the next few decades. The United Nations estimates that by 2050, it will reach 9.7 billion. The chance that the train will finally come to a stop and world population will stabilize or begin declining before 2100 is only 27 percent.

If we focus on such big-picture projections alone, though, we miss important nuances. Half of the population growth between now and 2050 will occur in nine countries, five of which are in Africa. Across the industrial world, meanwhile, birth rates are falling and life spans increasing. The number of people aged 65 and older in the world will more than double in the next 29 years, according to the U.N. The number aged 80 and older will almost triple. Many of those elderly will live in Europe, where by 2050 the 65 and over demographic is projected to account for more than a quarter of the population. Jack A. Goldstone, a political scientist at George Mason University and a global fellow of the Wilson Center in Washington, D.C., has called this disruption of the world order as we know it "the new population bomb."

Germany and Nigeria represent opposite extremes of this changing global dynamic. On one end is a wealthy but rapidly aging country where cities are shrinking and governments are facing ballooning pension costs. On the other is a youthful nation that will need to accommodate both more urban migrants and more babies—trends that could compound existing problems such as climate change and infectious diseases. Particularly in Nigeria, says Hans Groth, chair of the World Demographic and Ageing Forum in Saint Gall, Switzerland, history is no guide for what lies ahead: "We are not prepared as human beings to manage or accept such big changes."

GROWING PAINS

BY 2050 NIGERIA IS EXPECTED to overtake the U.S. to become the third most populous country in the world. Its population will nearly double, to 401.3 million, according to the U.N. Over the course of Saheed's young adult years, then, he will watch as Nigeria's already thin resources spread even thinner. "Think about it," says John Bongaarts of the Population Council in New York City. "Everything man-made in the country has to be duplicated. Every school, every clinic, every bridge."

In 2015 the U.N. Population Division revised upward its estimates for population growth in Africa. To some extent, the change reflected positive news. Thanks to advances in public health, including measures that reduced infant mortality and death from AIDs, life expectancy in sub-Saharan Africa had risen.

But the other half of the story is that although birth rates have declined, changes have not been as dramatic or rapid as many had hoped, and levels remain high compared with those in other countries. In sub-Saharan Africa, the total fertility rate—the average number of children a woman has over a lifetime—hovers at 4.7. In Nigeria, it is 5.4. The country could, in theory, gain from what is called a demographic transition—a phase during which fertility falls and a nation has a large number of working-age adults with few elderly and children to support. Countries that successfully complete a demographic transition, by lowering both birth rates and mortality while boosting education, employment and other drivers of economic development, can experience a "demographic dividend" that catapults them into the next level of development.

Demographers cite a range of possible factors for the slow changes in fertility in this region, from the lingering cultural expectations to a longer window during which women customarily have children. Says Akinrinola Bankole, a demographer at the Guttmacher Institute in New York City: "People are still thinking in terms of old-age security"—having a large number of children to care for them as they age. "They think less about the need to invest in the children who will provide that security."

High fertility rates will compound the daunting

Prop Styling by **Angela Campos** *Stockland Martel (preceding pages)*

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array of threats already facing Nigeria: poverty, hunger, the prevalence of communicable diseases and the effects of climate change. More than 260 million people in sub-Saharan Africa, or one in four, lack adequate food, and more than 30 percent of African children show signs of stunted growth, according to the U.N. Food and Agriculture Organization. As Saheed and his siblings age, the region will add hundreds of millions more mouths to feed. Among those now working to improve food security is the Alliance for a Green Revolution in Africa. Founded in 2006 and led for more than six years by former U.N. secretary-general Kofi Annan (Annan died in 2018), the organization lobbies for changes in agriculture policy and helps smallholder farmers obtain improved seeds, organic fertilizers and basic equipment. "The concentration of population growth in the poorest countries could make it harder for some countries to eradicate poverty, combat hunger and malnutrition, expand services in the area of education and health systems, and improve the provision of basic services and infrastructure," says François Pelletier of the U.N. Population Division.

Within countries such as Nigeria, moreover, population growth will not be evenly distributed. Birth rates are currently much higher in the north, which is largely resource-poor. As a consequence, growing numbers of northerners are moving toward Lagos—a change that is part of a larger global trend. Urbanization and overall growth are expected to add more than 2.5 billion people to the world's urban population by 2050, with around 90 percent of the increase happening in Asia and Africa.

CAN WE FEED THE PLANET WITHOUT DESTROYING IT?

"Yes. Here's what we need to do: reduce crop waste, consumer waste and meat consumption; integrate appropriate seed technologies and management practices; engage consumers about the challenges farmers face in both the developed and the developing world; increase public funding for agricultural research and development; and focus on advancing the socioeconomic and environmental aspects of farming that characterize sustainable agriculture."

Pamela Ronald
Professor in the Genome Center and the department of plant pathology at the University of California, Davis

Urbanization is often a positive phenomenon, accompanied by an increase in education, a decrease in the birth rate and steady economic growth. Well-planned cities reduce land use and boost energy efficiency. Henrik Urdal, a political scientist at the Peace Research Institute Oslo in Norway, and his colleagues have found that urbanization may even decrease the risk of conflict.

But the fact that countries like Nigeria are urbanizing at a much lower level of economic development than they once did means that by 2050 much of the world's population will be concentrated in cities unequipped to provide adequate health care, sanitation and other services. That could increase Saheed's exposure to infectious diseases, which can thrive in

Edwina Pickles *Getty Images*

SOME AFRICAN nations will undergo rapid population growth by 2050, putting pressure on food supplies and possibly leading to shortages. These mothers brought their children to be screened for malnutrition in Denjuok village, Akobo East County, South Sudan, during the 2014 hunger crisis.

Portrait by Kyle Hilton

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CAN WE AVOID A "SIXTH EXTINCTION"?

"It can be slowed, then halted, if we take quick action. The greatest cause of species extinction is loss of habitat. That is why I've stressed an assembled global reserve occupying half the land and half the sea, as necessary, and in my book *Half-Earth*, I show how it can be done. With this initiative (and the development of a far better species-level ecosystem science than the one we have now), it will also be necessary to discover and characterize the 10 million or so species estimated to remain; we've only found and named two million to date. Overall, an extension of environmental science to include the living world should be, and I believe will be, a major initiative of science during the remainder of this century."

Edward O. Wilson
University Research Professor emeritus at Harvard University

densely populated areas with large numbers of migrants. Urbanization is believed to have been a major contributing factor to the early spread of HIV/AIDS in Africa. By 2050 the heavily populated neighborhoods of Lagos could become hotbeds for tuberculosis and malaria.

As Nigeria moves up the economic ladder and more people buy cars and consume electricity, air pollution could pose another health threat. The rapid growth of megacities in Asia over the past few decades provides some guide of what could happen in Africa. Recent data from the Global Burden of Disease Study suggest that air pollution contributed to 1.85 million deaths in 2019 in China alone.

Ironically, if Nigeria manages to lower its birth rate, the shift could produce an unfortunate side effect. As the birth rate falls, the proportion of the total population composed of teenagers and young adults will increase. If the economy cannot provide enough jobs, Bongaarts says, "you have unemployed and underemployed young men who are unhappy. They are readily exploited, and they contribute to crime and lack of security."

To succeed in coming years, countries like Nigeria will need to simultaneously boost education, youth employment and access to family planning—a mammoth undertaking but one that is not impossible. Fifty years ago few foresaw the rapid decreases in fertility that have occurred in Bangladesh, Indonesia and Iran. If Saheed finds a job and gets married, he may decide to have fewer children than his parents so that he can afford their schooling costs. As more and more people like him do the same, Nigeria has a shot at turning a potential liability into an advantage and achieving a demographic dividend. Such population changes have been crucial to the economic ascent of other countries, including Brazil, China and South Korea.

IN THE OLD COUNTRY

A VERY DIFFERENT SORT OF SHIFT is under way in Germany. Lena was born in 1999, when the German economy was the engine for European economic growth and workers abounded. By 2050 the population is projected to fall from 83.8 million to 80.1 million. About 37 percent of Germans will then be 60 and older, whereas people aged 15 to 59, who make up most of the working-age individuals, will account for 50 percent, a 13 percent decrease from today. Parts of Germany already offer a preview of what is to come. In 2015 the septuagenarian mayor of Ottenstein, a community in the northwest of the country, announced that he would give away land to couples with young children. The goal: to keep the village's school open.

Germany's situation is reflected throughout Asia, Europe and Latin America. The U.N. projects that 26 countries, including Japan and Ukraine, could lose 10 percent or more of their populations by 2050. Media reports already make much of the declining birth rate in Germany and neighboring countries. By 2050 policy makers could be worrying about a sustained economic slowdown caused by a shortage of young workers and taxpayers.

Immigration could relieve some of that shortage. The U.N. predicts that between 2020 and 2050, Germany will be one of the world's top receivers of migrants. The hundreds of thousands of desperate Syrian families who have crossed into Europe to flee civil war, their possessions strapped to their back, have already brought this issue into focus. As the population continues to grow in sub-Saharan Africa—and especially if young adults like Saheed do not find jobs in their home countries—the number of migrants may increase, linking the futures of Germany and Nigeria. Pundits sometimes argue that this trend will help counteract the aging population. But, Goldstone notes, "it would take tens of millions of migrants to offset the shrinking youth cohorts in Germany, Netherlands and other low-growth countries"—and conversely, to relieve population pressure in fast-growing countries in sub-Saharan Africa.

That means that even with modest rates of immigration, the population of Leipzig might decline. In the process, the city may struggle to adapt its utility system and other services to less use, perhaps by raising fees—a change that would be borne by working-age people like Lena. The shrinking city could be an expensive one.

Germany is also likely to face new health challenges, as improvements in health and longevity shift its disease burden. Lena's parents, for example, are part of an "oldest old" group of people, aged 80 and older, that is projected to include 12.8 percent of Germans in 2050. They will be less likely than previous

Portrait by Kyle Hilton

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generations to die of cancer or a heart attack. But they will be more susceptible to dementia, a disease that is becoming more prevalent as life expectancy increases and that will only become more common unless a cure is found. "Before, people simply died before they contracted Alzheimer's," says Axel Börsch-Supan, director of the Munich Center for the Economics of Aging and project coordinator for the Survey of Health Ageing and Retirement in Europe, a longitudinal study of more than 140,000 Europeans aged 50 and older. "Now that doesn't happen."

Economically, aging in Western Europe is associated with some benefits. It is not only the result of low birth rates: it has also been brought on by marked jumps in life span and individual health and well-being. People are not merely living longer; they are staying healthy and able to work much longer as well. Over the past two decades life expectancy at birth in Germany increased by nearly four years to just over 81. Health metrics are improving across Europe, Börsch-Supan says: "Longevity is increasing linearly. There's no sign of the curve flattening out." (In the U.S., in contrast, discussion about the slower aging rate tends to obscure a disappointing trend in life expectancy, which has actually worsened, Börsch-Supan notes.)

In Europe, some say nothing short of a redefinition of what it means to be elderly is now required. Sergei Scherbov, a demographer at the International Institute for Applied Systems Analysis in Laxenburg, Austria, has proposed considering a person to be "aging" during only the last 15 years of life, as measured by a country's life expectancy at birth. Such a measure better reflects ability and health than the U.N.'s definition of aging as 60 and older, he says: "In the 1950s the oldest person to climb Mount Everest was 39 years old. [In 2013] a Japanese guy of 80 climbed it."

Indeed, pension systems are being overhauled across much of Europe. In Germany, the retirement age, which is now 65 and 10 months, will be gradually increased until it reaches 67 in 2031. But to provide for people like Lena's parents who are living past 80, the country's retirement age ultimately will need to be linked to life expectancy, as has happened in Norway and Sweden—a change that will likely prove unpopular. "The issue in Europe is that people love to retire early," Börsch-Supan says. "That is not sustainable."

LAGOS, Nigeria, is one of the fastest-growing cities in Africa, with its population poised to double in the next 25 years. This will make it the third-largest city in the world but without the infrastructure or resources of other cities.

Frans Lemmens *Alamy*

THE GRAVITY OF DEMOGRAPHY

THE FATES OF SAHEED AND LENA depend in no small part on what transpires now. By planning well for the future, demographers say, both Nigeria and Germany can tackle coming population changes. Demography, Goldstone says, is like gravity—you have to acknowledge its force and act accordingly. "If you manage to deal with gravity, you can make planes fly," he says. But you have to design your airplane well and fly it competently. "You can have a stable government and growing economy in the face of population growth or population decline. But you have to invest wisely, manage the economy well, educate the labor force to be more productive and plan for the welfare needs of different age groups as they change over time."

In a way, Nigeria and Germany can be seen as sitting at two ends of a global continuum. Between these two extremes are dozens of other nations whose role in the world will also shift with changes in population distribution—including the U.S., which will both age and grow in overall population. By acting now on issues such as health care, urban infrastructure, education, and food and pension security, countries across the spectrum can ensure better lives for generations to come.

Comprehensive efforts at maintaining global stability, meanwhile, will need to better involve populous emerging economies, among them Brazil, China, India and Mexico. That means reconfiguring global governing bodies such as the G7 and NATO so that they better reflect the changing face of the world—and ensuring that money flows toward the public health, resource and infrastructure challenges of the entire world, not just those of industrial nations. By thinking creatively and acting early and decisively, humanity might improve the quality of life for everyone, no matter where they are born. SA

Mara Hvistendahl is an investigative reporter with the *Intercept* and author of *Unnatural Selection: Choosing Boys over Girls, and the Consequences of a World Full of Men* (PublicAffairs, 2011). Her newest book is *The Scientist and the Spy: A True Story of China, the FBI, and Industrial Espionage* (Riverhead, 2020).

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RETURN OF THE GERMS

For more than a century drugs and vaccines made astounding progress against infectious diseases. Now our best defenses may be social changes

By Maryn McKenna

Illustration by Maria Corte

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IN 1972 THE DISTINGUISHED VIROLOGIST FRANK MACFARLANE BURNET LOOKED back over medical progress made in the 20th century with considerable satisfaction, surveying it for the fourth edition of the book *Natural History of Infectious Disease.* That very year routine vaccination against smallpox had ceased in the U.S., no longer needed because the disease had been eliminated from the country. During the previous year the combined vaccine against measles, mumps and rubella had been licensed, and four years before, in 1968, a pandemic of influenza had been quelled by a new vaccine formula. In 1960 Albert Sabin had delivered an oral vaccine against polio, and five years before that Jonas Salk had produced the first polio shot, preventing the dreaded paralysis that crippled children every summer. Since the time of World War II, drug development had delivered 12 separate classes of antibiotics, beginning with natural penicillin and ending seemingly forever the threat of deadly infections from childhood diseases, injuries, medical procedures and childbirth.

A few pages from the end of his book (co-authored with David O. White), Burnet made a bold prediction: "The most likely forecast about the future of infectious disease," he wrote, "is that it will be very dull."

Burnet was an experienced scientist who had shared the Nobel Prize in Physiology or Medicine in 1960 for pioneering ideas about the way people developed immune reactions. And at 73 he had lived through devastating epidemics, including the planet-spanning flu pandemic of 1918 while he was a university student in Australia. So he had seen a lot of advances and had played a role in some of them. "From the beginnings of agriculture and urbanization till well into the present century infectious disease was the major overall cause of human mortality," he wrote on the book's first page. "Now the whole pattern of human ecology has, temporarily at least, been changed."

Four years after Burnet made his optimistic prediction, the headmaster of a village school in what is now the Democratic Republic of the Congo collapsed with an unexplained bleeding disorder and died, the first recognized victim of Ebola virus. Nine years after his forecast, in 1981, physicians in Los Angeles and an epidemiologist at the U.S. Centers for Disease Control and Prevention diagnosed five young men in Los Angeles with an opportunistic pneumonia, the first signal of the worldwide pandemic of HIV/AIDS. In 1988 the gut bacterium *Enterococcus,* a common source of hospital infections, developed resistance to the last-resort antibiotic vancomycin, turning into a virulent superbug. And in 1997 a strain of influenza designated H5N1 jumped from chickens to humans in a market in Hong Kong, killing one third of the people it infected and igniting the first of multiple global waves of avian flu.

Those epidemics represent only a few of the infectious disease eruptions that now occur among humans every year, and efforts to stem them have taken on a renewed and urgent role in modern medicine. Some of these contagions are new to our species; others are resurgent old enemies. Sometimes their arrival sparks small outbreaks, such as an eruption of H7N7 avian flu in 2003 among 86 poultry-farm workers in the Netherlands. Now a never-before-seen illness, COVID-19, has caused a global pandemic that has sickened and killed millions.

None of these scenarios matches what Burnet envisioned. He thought of our engagement with infectious diseases simply as one mountain that we could climb and conquer. It might be more accurate to understand our struggle with microbes as a voyage across a choppy sea. At times we crest the waves successfully. In other moments, as in the current pandemic, they threaten to sink us.

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JONAS SALK injects a child with the polio vaccine in the 1950s, a victory over a terrifying disease.

Getty Images

IT IS DIFFICULT, under the weight of the novel coronavirus, to look far enough back in American history to perceive that—surprisingly—freedom from infectious disease was a part of the early New England colonists' experience. Beginning in the 1600s, these people fled English and European towns drenched in sewage and riven with epidemics where they might be lucky to live to their 40th birthday. They found themselves in a place that felt blessed by God or good fortune where a man—or a woman who survived childbearing—could, remarkably, double that life span.

This was true, of course, only for the colonizers and not for the Indigenous Americans whom they displaced. The Spanish who arrived in Central and South America about a century earlier, and other European colonists who followed to the North, brought diseases so devastating to the precontact population that researchers have estimated 90 percent of the existing inhabitants were killed. Nor was it true for enslaved people brought to American shores, whose lives were cut short by abuse in the South's plantation system.

New Englanders before the 19th century, however, "had a very strange and unusual experience with infectious diseases," says David K. Rosner, a historian and co-director of the Center for the History and Ethics of Public Health at Columbia University. "When infections hit, and they did hit—smallpox, yellow fever—they were largely very localized and of relatively short duration."

At the time and through the early 1800s, disease was understood as a sign of moral transgression, a visitation meant to guide an erring population back to righteousness. In 1832 the edge of a worldwide pandemic of cholera washed up on the East Coast of the U.S., carried into port cities by ships plying trade routes. The governors of a dozen states declared a mandatory day of prayer and fasting. In New York the well-off fled the city for the socially distanced countryside, blaming the poor left behind for their own misfortune. A letter preserved by the New-York Historical Society, written by its founder, captures the callousness of some wealthy people: "Those sickened … being chiefly of the very scum of the city, the quicker [their] dispatch the sooner the malady will cease."

Cholera was a global devastation, but it was also a doorway to our modern understanding of disease. Dogma held that its source was miasmas, bad air rising from rotting garbage and stagnant water. As late as 1874—20 years after physician John Snow traced the source of a London cholera outbreak to a neighborhood's well and halted it by removing the pump handle—an international conference on the disease declared that "the ambient air is the principal vehicle of the generative agent of cholera." It was not until 10 years later, when bacteriologist Robert Koch found identical bacteria in the feces of multiple cholera victims in India and reproduced the bacterium in a culture medium, that a microbe was proved to be the cause. (Koch was not aware that Italian bacteriologist Filippo Pacini had made the same observations in the year when Snow took the handle off the pump.)

This explanation for the source of cholera became one of the foundations of germ theory. The concept that disease could be transmitted and that the agents of transmission could be identified—and possibly blocked—transformed medicine and public health. The idea ignited a burst of innovation and civic commitment, a drive to clean up the cities whose filthy byways allowed disease-causing microbes to fester. Towns and states established municipal health departments and bureaus of sanitation, built sewer systems and long-distance water supplies, regulated food safety and ordered housing reform.

These improvements tipped industrial nations toward what would later be called the epidemiological transition, a concept coined by Abdel Omran in 1971 to describe the moment when deadly infections would retreat and slow-growing chronic diseases could become society's priority. Science started a seemingly unstoppable climb up the mountain of 20th-century achievement: viral identification, vaccine refinement, the development of antibiotics, the introduction of immunotherapies, the parsing of the human genome. Life expectancy in the U.S. rose from an average of 47 years in 1900 to 76 years toward the end of the century. The last case of smallpox, the only human disease ever eradicated, was recorded in 1978. The Pan American Health Organization declared its intention to eliminate polio from the Americas in 1985. The future seemed secure.

IT WAS NOT, OF COURSE. In October 1988, in this magazine, Robert Gallo and Luc Montagnier wrote: "As recently as a decade ago it was widely believed that infectious disease was no

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longer much of a threat in the developed world. The remaining challenges to public health there, it was thought, stemmed from noninfectious conditions such as cancer, heart disease and degenerative diseases. That confidence was shattered in the early 1980's by the advent of AIDS."

Gallo and Montagnier were co-discoverers of the HIV virus, working on separate teams in different countries. When they wrote their article, there had been more than 77,000 known cases of AIDS on the planet. (There are 76 million now.) As the researchers noted, recognition of the new illness punctured the sense of soaring assurance that infectious diseases had been conquered. Four years after Gallo and Montagnier wrote, 19 eminent scientists gathered by the Institute of Medicine (now part of the National Academies of Sciences, Engineering and Medicine) broadened the point in a sober book-length assessment of what they termed "emerging infections." Scientists and politicians had become complacent, they said, confident in the protection offered by antibiotics and vaccines and inattentive to the communicable disease threats posed by population growth, climate warming, rapid international travel, and the destruction of wild lands for settlements and mega-farms.

"There is nowhere in the world from which we are remote," the group warned, "and no one from whom we are disconnected." The scientists recommended urgent improvements in disease detection and reporting, data sharing, lab capacity, antibiotics and vaccines. Without those investments, they said, the planet would be perpetually behind when new diseases leaped into humans and catastrophically late in applying any cures or preventions to keep them from spreading.

Their warning was prescient. At the time of their writing, the U.S. was recovering from its first major resurgence of measles since vaccination began in the 1960s. More than 50,000 cases occurred across three years when epidemiological models predicted that there should have been fewer than 9,000. The year after the Institute of Medicine's report was published, five healthy young people collapsed and died in the Southwestern U.S. from a hantavirus passed to them by deer mice. In 1996 researchers in Chicago discovered that antibiotic-resistant *Staphylococcus* bacteria had leapfrogged from their previous appearances in hospitals into everyday life, causing devastating illnesses in children who had no known risks for infection. Across health care, in urban life and in nature, decades of progress seemed to be breaking down.

"We forgot what rampant infectious disease looked like," says Katherine Hirschfeld, an associate professor of anthropology at the University of Oklahoma, who studies public health in failing states. "Science built us a better world, and then we got cocky and overconfident and decided we didn't have to invest in it anymore."

But unlike illnesses in the past—cholera epidemics in which the rich fled the cities, outbreaks of tuberculosis and plague blamed on immigrants, HIV cases for which gay men were stigmatized—infections of today do not arrive via easy scapegoats (although jingoistic politicians still try to create them). There is no type of place or person we can completely avoid; the globalization of trade, travel and population movement has made us all vulnerable. "We cannot divide the world anymore into countries that have dealt with infectious disease successfully and those that are still struggling," Hirschfeld says. "Countries have enclaves of great wealth and enclaves of poverty. Poor people work for rich people, doing their landscaping, making things in their factories. You cannot wall off risk."

TENTS OUTSIDE Los Angeles County–U.S.C. Medical Center were set up to screen a large surge of COVID-19 patients.

Valerie Macon *Getty Images*

THE PLANET THAT SLID DOWN the far side of the 20th century's wave of confidence is the planet that enabled the spread of COVID-19. In the five years before its viral agent, SARS-CoV-2, began its wide travels, there were at least that many warnings that a globally emergent disease was due: the alerts appeared in academic papers, federal reports, think-tank war games and portfolios prepared at the White House to be handed off to incoming teams. The novel coronavirus slipped through known gaps in our defenses: it is a wildlife disease that was transmitted to humans by proximity and predation, spread by rapid travel, eased by insufficient surveillance, and amplified by nationalist politics and mutual distrust.

We were unprepared, with no vaccine or antiviral. In past epidemics of coronaviruses, such as SARS in 2003 and MERS in 2012, scientists had begun work on vaccines, but funding and interest dried up as the outbreaks waned. If research had continued, the current emergency might have been shortened. Preventions and pharmaceuticals were the stellar achievements of the 20th century, but among scientists and physicians who deal with emerging diseases, there is a sense that attempts to repeat such successes will not be sufficient to save us. What is equally urgent, they argue, is attending to and repairing the conditions in which new diseases arise.

"Poverty has more impact than any of our technical interventions," says Peter J. Hotez, a physician and vaccine developer and founding dean of the Baylor University National School of Tropical Medicine. "Political collapse, climate change, urbanization, deforestation: these are what's holding us back. We can develop all the vaccines and drugs we want, but unless we figure out a way to deal with these other issues, we'll always be behind."

Evidence for Hotez's statement is abundant in the toll of those who have suffered disproportionately in the current pandemic—people who rely on urban transit, live in public housing

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or nursing homes, or are subject to the persistent effects of structural racism. What has made them vulnerable is not primarily a lack of drugs or vaccines. "My hospital is buried in COVID-19 patients," said infectious disease physician Brad Spellberg, chief medical officer at Los Angeles County–University of Southern California Medical Center, one of the largest public hospitals in the U.S., in mid-2020. "We serve a community of people who cannot physically distance. They are homeless, they are incarcerated, they are working poor living with a family of four in one room."

The term often used to denote what Hotez and Spellberg are describing is "social determinants of health." It is an unsatisfying phrase that lacks the muscular directness of "shot" and "drug," but it is a crucial and also measurable concept: that social and economic factors, not just medical or innate immunological ones, strongly influence disease risk. Negative social determinants include unsafe housing, inadequate health care, uncertain employment and even a lack of political representation. They are the root cause of why the U.S., the richest country on Earth, has rapidly rising rates of hepatitis, sexually transmitted diseases, and parasitic and waterborne infections, as reported in *Scientific American* in 2018—infections that first arise among the poor and unhoused but then migrate to the wealthy and socially secure. As research by British epidemiologists Richard Wilkinson and Kate Pickett has shown, unequal societies are unhealthy ones: the larger the gap in income between a country's wealthiest and poorest, the more likely that country is to experience lower life expectancy and higher rates of chronic disease, teen births and infant mortality. That phenomenon goes a long way toward explaining why COVID-19 wreaked such devastation in New York City, one of the most financially unequal cities in the country, before the city government applied the brute-force tool of lockdown and regained control.

Lockdowns are effective, but they cannot be sustained indefinitely, and they carry their own costs of severe mental health burdens and of keeping people from health care not related to the virus. And although quarantines may keep a pathogen from spreading for a while, they cannot stop a virus from emerging and finding a favorable human host. What might prevent or lessen that possibility is more prosperity more equally distributed—enough that villagers in South Asia need not trap and sell bats to supplement their incomes and that low-wage workers in the U.S. need not go to work while ill because they have no sick leave. An equity transition, if not an epidemiological one.

IT IS DIFFICULT TO ENUMERATE features of this more protected world without them sounding like a vague wish list: better housing, better income, better health care, better opportunities. Still, changes that some places around the globe enacted as defenses against current infection might make future infections less likely. Closing streets to encourage biking as Lisbon did, turning parking spaces into café spaces as has happened in Paris, and creating broadband capacity for remote working and shifting health care to telemedicine, both done in the U.S.—these adaptations sound like technological optimism, but they could help us construct a society in which people need not crowd into unsafe urban spaces and in which income can be detached from geography.

It is certainly also necessary to re-up the investments in preparedness that the Institute of Medicine rebuked the U.S. for dropping almost 30 years ago. "We need to think about this with an insurance mindset," says Harvey Fineberg, a physician and president of the Gordon and Betty Moore Foundation, who was president of the institute when it prepared a 2003 follow-up to its warning. "If your house doesn't burn down, you don't bang your head on the wall on December 31 and say, Why did I buy that fire insurance? We buy insurance proactively to prevent the consequences of bad things that happen. That is the mindset we need to adopt when it comes to pandemics."

The U.S. responded to the coronavirus with an extraordinary federally backed effort to find and test a vaccine in time to deliver 300 million doses by early 2021. This was a tremendous aspiration given that the shortest time in which a vaccine has ever been produced from scratch is four years (that vaccine was against mumps). There is no question that medical science is much better equipped than it was when Burnet was writing in the 1970s; *Natural History of Infectious Disease* came out before monoclonal antibody drugs, before gene therapy, before vaccines that could target cancers rather than microbes. The apotheosis of such work may be the development of chimeric antigen receptor T cell, or CAR-T, therapies, which debuted in 2017 and reengineer the body's own specialized immune system cells to combat cancers.

But CAR-T is also a sign of how concern for infectious diseases has slid into a trough of disregard. CAR-T therapies help a rare few patients at an extraordinary cost—their price before any insurance markup hovers around $500,000—whereas antibiotics, which have saved millions from death by infection, have slipped into peril. Most of the major companies that were making antibiotics in the 1970s—Eli Lilly, AstraZeneca, Bristol-Myers Squibb and Novartis, among others—have left the sector, unable to make adequate profits on their products. In the past few years at least four small biotechnology companies with new antibiotic compounds went bankrupt. This happened even though antibiotics are a crucial component of medicine—and now it is clear that they will be needed for some COVID-19 patients to cure severe pneumonias that follow the initial viral infection.

Better structures for preparedness—disease surveillance, financial support for new drugs and vaccines, rapid testing, comprehensive reporting—will not by themselves get us to a planet safer from pandemics any more than car-free streets and inexpensive health care will. But they could give us a place from which to start, a position in which we are relatively more secure as a society, relatively more safe from known diseases, and more likely to detect previously unknown threats and to innovate in response to them.

Rosner, the historian, looks back to the explosive energy of the Progressive Era and wonders what a post-COVID equivalent might be. "In the 19th century we built entire water systems, we cleaned every street in cities," he says. "We have so constricted our vision of the world that it seems we can't address these issues. But there are moments in past crises when we have let the better angels in our society come to the fore: after the Great Depression, in the New Deal. It's not impossible." SA

Maryn McKenna is a journalist specializing in public health, global health and food policy and a senior fellow of the Center for the Study of Human Health at Emory University. She is author most recently of *Big Chicken: The Incredible Story of How Antibiotics Created Modern Agriculture and Changed the Way the World Eats* (National Geographic Books, 2017).

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CATCHING FEVER

Climate change is accelerating the spread of disease—and making it much harder to predict outbreaks

By Lois Parshley

Photographs by Sean McDermott

IN SOUTH AFRICA, researchers are trying to understand where the Rift Valley fever virus is lurking between outbreaks.

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KOBUS STEENKAMP'S FARM SPRAWLS along a dirt road in South Africa's central plains, where the sky makes everything seem small. Steenkamp woke up here one morning after the rains in 2010 to find something strange happening with his sheep. "You could see there's blood at their backs," he recalls. All his pregnant ewes were losing their lambs.

It was every farmer's nightmare: his herd had been infected by Rift Valley fever, a mosquito-borne virus that causes abortion and death in livestock and wildlife and can be transmitted to humans. Within days, dozens of people had also been infected. Most displayed only flulike symptoms, but in some cases, the illness escalated into a severe hemorrhagic fever akin to Ebola.

A similar scene was unfolding across the region. The survival rate in adult animals is as low as 10 percent, and nearly 100 percent of infected sheep abort their pregnancies. Dead lambs and calves were left bloating in fields until the state veterinary team came to collect and incinerate the carcasses. By the time the outbreak was under control, almost 9,000 animals and 25 people had died. Neighboring countries, such as Zimbabwe and Namibia, banned South African meat, shattering the livestock industry.

Ever since the virus was first identified in 1931 in Kenya's Rift Valley, outbreaks like this one had been confined to southern and eastern Africa. But in 1977 the disease migrated north through increased trade on the Nile River, causing what the World Health Organization called an "explosive outbreak" in Egypt. Then, in September of 2000, it jumped to the Arabian Peninsula, arriving in Saudi Arabia and Yemen—sparking anxiety that Europe and North America were next. The idea that the virus could spread across these continents in just a few years is not some hyperbolic scenario. Rift is transmitted through a broader range of hosts and vectors than West Nile virus, which arrived in New York City in 1999 and spread across the U.S. in less than six years. The U.S. Department of Agriculture has taken notice, naming Rift the third most dangerous animal pathogen, behind only bird flu and foot-and-mouth disease. But health officials are not just worried about its impact on animals and agriculture. Zoonotic diseases—infectious illnesses such as Rift that begin in animal populations and jump to humans—are the biggest risk for epidemics and pandemics. They have been responsible for some of history's worst, including bubonic plague and Ebola.

The fear of Rift growing into a global pandemic highlights that public health researchers still don't know how to effectively predict disease outbreaks, which have devastating consequences on health, economies and political stability. Meanwhile the threat of emerging zoonotic diseases is expanding—and often in unforeseen ways. Scientists are only just beginning to understand how outbreaks correlate with shifting weather patterns—a hallmark of climate change. As they do, the picture is becoming more complicated. Worldwide, temperatures are changing faster than anyone previously predicted, and as a result, habitats are, too—altering the ranges of animals, viruses and, increasingly, humans. These complex relationships are now more volatile than ever, leading one recent *Lancet* paper to conclude that climate change is "the biggest global health threat in the 21st century" and yet another in the *Lancet* to suggest that it "threatens to undermine the last half century of gains in development and global health."

Global warming and extreme weather patterns are already dramatic forces on public health. Intensified floods, droughts and storms are changing how humans can use land and, ultimately, where we can live. As climatologists race to model what has changed so that coastal communities, for instance, can adapt to rising seas, epidemiologists are also realizing how critical it is to develop epidemic-prediction tools that incorporate new and impending weather patterns. Such research is a matter of equity between developing and developed nations. And in an ever more globalized world, it may be a way of averting a future of unprecedented pandemics.

AN INTERCONNECTED APPROACH

TO GET TO STEENKAMP'S FARM, biologist Ettienne Theron has been driving for hours toward an endless horizon. His truck, loaded with coolers full of blood, bounces down a crumbling highway that is flanked by open grassland. These velds are where the last several Rift epidemics in South Africa began. It's here, in an area larger than the size of Maryland, that Theron and dozens more researchers are collecting and analyzing data for a project run by EcoHealth Alliance, a global nonprofit that focuses on pandemic prevention. [*Editor's Note: This story was reported before the COVID pandemic drew more attention to EcoHealth Alliance, which was a partner with the Wuhan Institute of Virology as part of its work around the world.*]

The challenge for scientists and policy makers alike is to learn how to intervene before pathogens infect people. Once a pandemic emerges, said Eco-

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Health president Peter Daszak in a 2015 video, "all you can really do is put out the fire." The goal of this five-year, multidisciplinary project is to examine, for the first time, exactly how climate affects Rift Valley fever in southern Africa. In doing so, researchers hope to develop a data-based model that actually predicts outbreaks before they happen, a stepping-stone to making models for other viruses as well. Notably, the U.S. Department of Defense has funded the entire project. Rift can easily be used as an aerosol and was weaponized by both the U.S. and the Soviet Union during the cold war. But bioterrorism is only one concern; keeping diseases from reaching the U.S.'s shores—and knowing how to react if they do—is increasingly a matter of national security.

Theron finally arrives at an unmarked gate, and the team members, who collectively speak nine of the languages represented in the Free State province, pile out of the truck and pull on muck boots. Using a random distribution of GPS points, the researchers have reached an agreement with 361 isolated farms like Steenkamp's, where, for two years in a row, they have taken blood samples from livestock and farm staff to test for Rift antibodies, trying to understand where the virus might be lurking when no one is reporting active cases.

Steenkamp himself was infected during an outbreak in the 1970s, and according to the WHO, as many as 10,000 people a year contract the virus. That number will most likely rise. A 2016 study published in *Emerging Microbes & Infections* reports that the "explosive nature" of recent epidemics suggests the virus has mutated into a more infectious and severe strain. As it migrates to new places, the virus may evolve further, becoming even more dangerous.

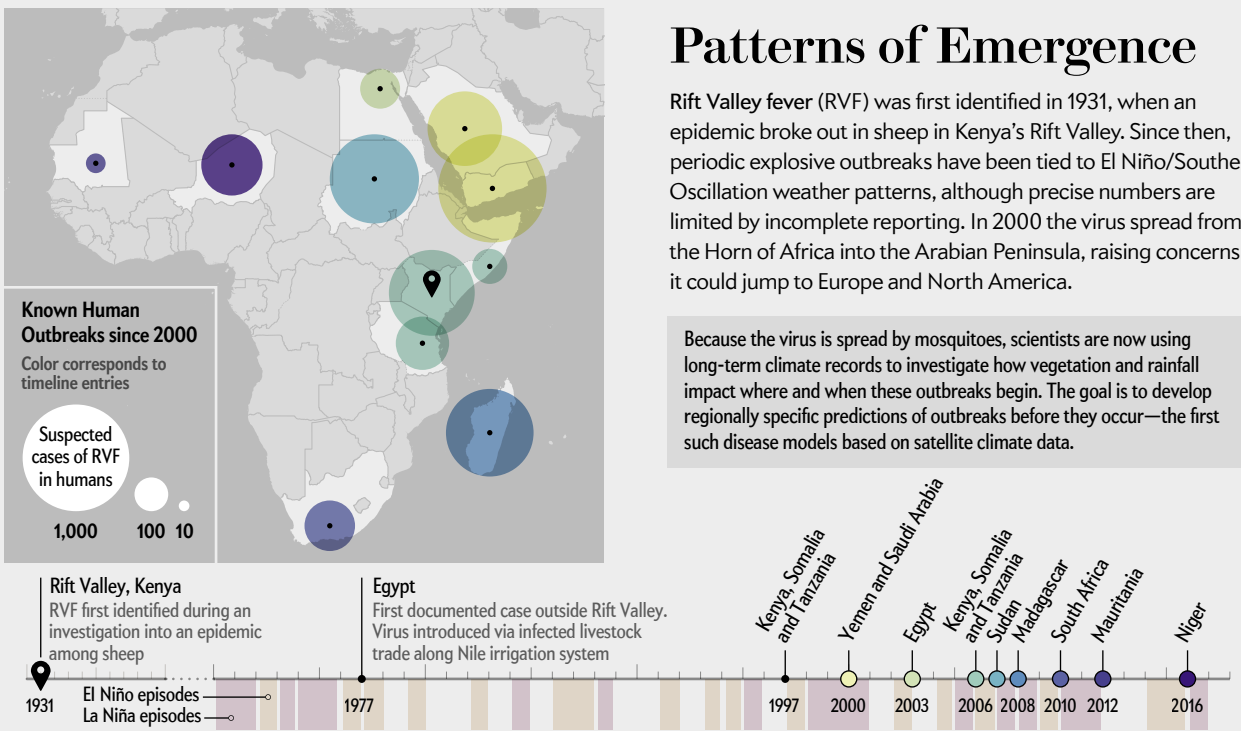
As the farm crew maneuvers sheep into a corner of a rusted corral, field coordinator Claudia Cordel unpacks an arrangement of empty vials, data sheets, latex gloves and a sharps box on a folding card table. A farm worker grabs an ewe. It bleats while Cordel draws blood from its jerking neck. In South Africa, *Aedes mcintoshi* mosquitoes are thought to be the main carrier of Rift. The females transmit the virus directly to offspring, and their eggs can survive years of drought—a typical occurrence in this region. When the new generation of infected mosquitoes eventually hatch, they transmit the virus to livestock and wildlife alike. The virus amplifies in these hosts, so that when wider-ranging mosquitoes, such as *Culex* and *Anopheles,* bite infected animals, the original outbreak transforms into a swift-moving epidemic.

In another corral, Cordel wipes a cow's anus before piercing its tail vein. The cow lows and lets loose a squirt of green liquid toward her face. Cordel explains that though the basics of the virus transmission are known, "we have no idea how wildlife impacts people or livestock, or vice versa," adding that the feedback cycles are completely undocumented. That is why the EcoHealth team wants to get a more granular look at the interactions of weather, plants, insects, animals and people. At 22 research sites around the Free State and Northern Cape provinces, researchers trapped mosquitoes to search for the virus, studying soil composition and

Patterns of Emergence

Rift Valley fever (RVF) was first identified in 1931, when an epidemic broke out in sheep in Kenya's Rift Valley. Since then, periodic explosive outbreaks have been tied to El Niño/Southern Oscillation weather patterns, although precise numbers are limited by incomplete reporting. In 2000 the virus spread from the Horn of Africa into the Arabian Peninsula, raising concerns it could jump to Europe and North America.

Because the virus is spread by mosquitoes, scientists are now using long-term climate records to investigate how vegetation and rainfall impact where and when these outbreaks begin. The goal is to develop regionally specific predictions of outbreaks before they occur—the first such disease models based on satellite climate data.



Sources: World Health Organization and Centers for Disease Control and Prevention (*outbreak data*); National Weather Service (*El Niño and La Niña data*)

Graphic by Tiffany Farrant-Gonzalez

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vegetation and setting up mini weather stations to monitor local conditions in conjunction with satellite data. This kind of comprehensive approach, which required dozens of experts in epidemiology, ecology, climatology, veterinary medicine and entomology, is both costly and relatively rare. But it may be the future of understanding how infectious diseases emerge and spread.

"It makes sense that the health of an animal population is related to the health of the human population," says Melinda Rostal, one of the project's investigators. Animals often serve as early-warning signs of a new outbreak; in 2017 in Brazil, for example, local monkey populations were nearly wiped out eight months before a yellow fever epidemic. But structuring research around interactions among people, animals and the environment has only recently gained traction in the global health community. This strategy, first defined by epidemiologist Calvin Schwabe in 1964 and now called "One Health," is an increasingly popular intellectual framework for epidemiology. As far back as 400 B.C., Hippocrates understood that the environment—including weather—impacts disease, but systematically bringing together multidisciplinary research to better understand complex systems is relatively new. The U.S. Centers for Disease Control and Prevention did not establish a One Health office until 2009, when officials acknowledged that changing environmental interactions "have led to the emergence and reemergence of many diseases." Pursuing One Health research is expensive up front, but in the long run, it can actually be more efficient: by sending out collaborative teams instead of funding individual research trips, the EcoHealth Rift project reduced the cost of transportation for its study by 35 percent.

MOSQUITOES CAN LIVE IN AN AREA THE SIZE OF A SUBURBAN BACKYARD, SO REMOTELY SENSED DATA DO NOT GET AT THE SCALE WITH WHICH PATHOGENS INTERACT WITH THEIR HOSTS.

The longtime absence of this style of coordination is partly why the global health community is still playing catchup on emerging diseases. Consider Zika, for example: although it was first identified in Uganda in 1947, it was largely ignored until it began tearing through the Americas in 2015. Such diseases often lack attention when they first emerge because they affect the poorest populations of the world, meaning they are generally not profitable for pharmaceutical development. The result is that these so-called neglected tropical diseases, according to the CDC, have already cost 57 million years of life lost prematurely. So as one of the largest One Health projects to date, EcoHealth's Rift work is an important case study: Can broad, multidisciplinary research projects fill this dangerous knowledge gap?

As the setting sun turns the grass gold, Cordel and Theron finish the farm visit by checking on a weather station, where a lonely wind propeller ticks above barbed wire. Satellite data from NASA suggest that this region will see altered weather patterns, changing its risk of both Rift and other infectious diseases. Transmission is a complicated thing, but undoubtedly a key factor in future disease control will be understanding the implications of our changing climate.

FORECASTING CLIMATE ON A BACKYARD SCALE

ON THE LONG DRIVES between field sites, dead sunflowers droop under a relentless sky. South Africa has been in a drought for a few years, and the red soil has frazzled into puzzle pieces. Drought itself is a standard feature of El Niño weather patterns, and when La Niña eventually comes and completes the cycle, the area will see heavy rains. But these cycles, while typical, are intensifying because of climate change, becoming drier and wetter, explains Assaf Anyamba, a research scientist at the NASA Goddard Space Flight Center. (In March 2018 South Africa declared a "national state of disaster" over its prolonged drought. Cape Town was at risk of running out of water during the worst drought in 400 years.) Even as conditions grow more extreme, Anyamba says, the downpour associated with this rain pattern—known as the El Niño/Southern Oscillation (ENSO)—and the vegetable life that downpour creates are what makes it possible to predict the hatching of Rift-infected mosquitoes. In fact, Anyamba was able to successfully predict the 2006 and 2007 Rift outbreak in East Africa by adding satellite climate models to the mix instead of just relying on regional weather patterns. "To my knowledge," he says, "this is the only system of its kind for any disease."

With that promising model in hand, Anyamba looked to southern Africa and the Arabian Peninsula. If he could apply the tools he used in eastern Africa to predict Rift outbreaks elsewhere, perhaps he could expand the model to other diseases. But so far his Rift models have failed in South Africa. As the climate expert on the EcoHealth study, Anyamba is now trying to figure out why. Satellite data that show and forecast global weather patterns

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make it easier to predict changes with vegetation and insects. The downside is that this big-picture view is fairly imprecise. When researchers combine climate models with more granular regional data such as vegetation coverage, they are dealing with two different scales. Anyamba's eastern African satellite models relied on a vegetation index, for example, that did not reflect southern African plant species. Other factors that impact disease, such as the spread of vectors, can be even finer-grained. Many mosquitoes live in an area the size of a suburban backyard, so even remotely sensed data do not get at the scale with which pathogens interact with their hosts. Although weather has long been linked with disease—think "flu season"—it is this level of specificity that makes predicting outbreaks so challenging. A one-size-fits-all template will not work.

Anyamba's new tactic is to use the information the EcoHealth team gathers on mosquitoes and vegetation in South Africa to build a more customized prediction model for the region. Climate change may eventually make the Free State province drier, which would help prevent Rift outbreaks. Other parts of the country, however, will likely get warmer and wetter, increasing Rift and the other diseases that floods tend to foster. Learning how to build more regionally sensitive tools will help scientists understand how disease burdens may change, both locally and globally.

Getting there is a matter of urgency. While it is rare to find sweeping conclusions in epidemiology, it is clear that greater climate variability—and therefore greater disease fluctuation—is already here. The first conclusive evidence of the trend was likely initially reported in a 2002 study published in the *Proceedings of the National Academy of Sciences USA,* which looked at cholera prevalence in Bangladesh over a 70-year period and found that "warming trends over the last century are affecting human disease." Mosquito and other insect habitats have expanded because of warming, exposing new populations to viruses. Preliminary research shows that malaria, for example, is globally on the rise. A temperature bump of just two degrees Celsius—a mark we are quickly approaching—would expand the number of people at risk of malaria by several hundred million, according to the WHO. Strangely, places that are now ideal climates for malaria may see less of it as they warm; prevalence will likely occur where malaria has not yet arrived, such as the U.S.

This type of vexing nuance has troubling consequences. Take bluetongue virus, a highly lethal ruminant disease that is spread by biting midges called *Culicoides*. Historically it was confined to tropical regions, but by 2006 there was enough warming in western Europe that some of those midges moved north and infected animals. Scientists were surprised when another kind of midge then picked up the virus from sickened sheep and carried it all the way to Norway. Corrie Brown, a veterinary pathologist at the University of Georgia, says bluetongue is a prime example of how climate change introduces species to one another for the first time—expanding how diseases can spread in an unpredictable manner.

AT ONE OF 22 WEATHER STATIONS set up by the EcoHealth Alliance's Rift Valley fever project, Zihona Gqalaqha, then a graduate student at the University of the Free State in South Africa, collects data on soil moisture.

Experts disagree on the best way to handle these risks. The U.S. Agency for International Development supports a strategy that focuses on identifying new pathogens, but Brown thinks merely discovering new viruses is an inefficient use of limited research funding. "I can see how very good it'd be for the investigators because they'd get a lot of papers published," Brown says, but she is bearish on its value in preventing people from getting sick. Instead Brown and others who advocate for a One Health approach think strengthening local infrastructure—building monitoring and surveillance systems and training community nurses, for instance—is the most effective way to grapple with the fickle burdens of emerging diseases. "If we improve the level of expertise of health-care professionals all around the world, we'll be in a better place," she says.

Local detection systems are especially important in places where humans are the ones who have moved into new environments, exposing themselves to diseases they have not yet encountered. "In an unchanging world, you don't see a lot of emerging disease," says William Karesh, an epidemiologist and the Rift study's principal investigator. "It's when systems alter that microbes reveal themselves in new ways." Often epidemics and their ripple effects

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"happen at the edge, where humans are living next to wild spaces," says Carrie La Jeunesse, a former AAAS Congressional Science & Technology Policy Fellow who worked on Ebola. Since 2009 USAID has developed a heat map for emerging diseases with pandemic potential; it is remarkably similar to maps of regions threatened by human impact. In a 2012 paper published in the *Lancet,* Karesh and his colleagues summarized these findings by explaining that "many zoonoses can be linked to large-scale changes in land use."

That is certainly true in South Africa. "We actually farm with arboviruses," the viruses transmitted by arthropods such as ticks, says Alan Kemp, an entomologist on the EcoHealth project. "With Rift, it's almost certain that thanks to cattle breeding and importing exotic breeds that aren't resistant, we're actually literally farming Rift." He sighs and says, "To be honest, to a large extent, we're guilty of our own demise."

THE HUMAN STRAIN

THE THOUSANDS of blood samples EcoHealth has procured end up under the fluorescent gleam of a biosafety level–four laboratory in Johannesburg. Like Ebola, work with Rift is allowed only in the highest level of containment, and investigator Janusz Paweska wears a pressurized protective suit to examine Rift specimens under a microscope. "Some scientists refer to nature as the most terrible bioterrorist, which I dislike," says Paweska from his office, after he has been through the elaborate decontamination process. As head of South Africa's Center for Emerging Zoonotic and Parasitic Diseases, he does not mince words: "Who creates this environment for emergence? You can't accuse nature. Uncontrolled urbanization, climate change, poverty—that's not nature. The answer is that *we* create the situation for the emergence of many of these diseases."

Arguably poverty is already the greatest risk factor for getting sick. "The major trigger or determinant of health is economic," says Antoine Flahault, director of the Institute of Global Health in Geneva, explaining that an unequal distribution of health care is the primary problem. The WHO estimates that in low-income countries, diseases of poverty that are often preventable or treatable (think diarrhea, malnutrition and parasitic infections) account for 45 percent of deaths. Climate change is expected to drive at least 122 million people into extreme poverty in the next few decades, forcing many to leave their homes and leading to rapid urbanization, all of which tends to foster disease. Flahault expects that one of the major disease contributions of climate change will come from these consequences of forced migration. "We can expect a huge impact on health, not just because of direct impact on disease but because of the indirect economic impacts, which may be very severe," Flahault says.

But when countries with limited resources are asked to prepare for a future potential threat, often at the cost of immediate problems, "it's a hard trade-off," explains Susan Scribner, director of the Preparedness & Response project at the global development firm DAI. "What we do is called health, but in some ways, a lot of it has to do with good governance," she says. That is why projects such as the Rift study could be particularly powerful: they provide data to many different stakeholders spanning agriculture, health and defense.

Anyamba, EcoHealth's climate expert, sees the Rift study as the way of the future. "I envision more projects involving climate data, fused with advanced analytics and machine-learning technologies, that will begin to answer some questions [about] why particular disease outbreaks occur," he says. Policy makers may be juggling other priorities, but it is important that they understand this science, Scribner says, "because when a pandemic hits, scientists aren't the ones in charge of the response." In fact, the DOD's Defense Threat Reduction Agency funded similarly comprehensive research to predict and map areas at risk for chikungunya, another mosquito-borne viral infection. There is a long list of diseases, such as yellow fever, dengue and even rabies, that would benefit from the kind of resources the DOD can bring to bear.

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FIELD TEAM MEMBERS take blood samples from farm workers and livestock to test for Rift Valley fever antibodies. Researchers are trying to understand how the virus is maintained between outbreaks.

But funding—and the politics that go into deciding whose research gets it—plays a critical role in which diseases are deemed worthy of attention. In the current political climate, support for the long-term resources that logistically complex projects (such as the Rift study) require is actively disappearing. Just as we are beginning to realize how urgent a collaborative approach to disease might be, the CDC has faced massive threats to its global health security efforts. Funding global health is a complex endeavor managed by multiple agencies in the U.S. alone. Experts at the Brookings Institution think tank have written that it could be "devastating for global health," damaging economic growth as well as weakening international stability.

But the importance of doing this kind of intensive fieldwork continues. Amid this limbo, EcoHealth's sweeping fieldwork presses on. Early one morning during its collection process, the team pulls up to a private game reserve near Mokala National Park to chase down kudu, a type of African antelope. Wildlife can both carry and transmit Rift to livestock and humans, but their blood samples are especially tricky to obtain. A helicopter arrives to lend a hand. Soon trucks are bouncing over the grass, a cloud of dust marking progress toward the herd. Beyond the front tires, the animals swerve and leap. They gleam like ribbons. The stillness when one is tranquilized from the sky is shocking. The scientists work quickly, sliding around a maze of arms and legs with syringes and vials. The kudu will wake in a matter of minutes.

After the blood is collected, the researchers begin their decontamination procedures, scrubbing dust off their boots to avoid spreading any diseases to the next property they visit. Nearby, a caged lion lounges in a puddle of sunshine, awaiting the delivery of his next meal. He yawns at the stream of passing cars. Once this bushveld stretched wild over half of the country, but today it has been largely partitioned off and contained behind tall fences. There are few places now where wildlife are still able to wander free. The world has already changed, even if we do not yet know the consequences. SA

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THE INFORMATION MANIPULATORS

By moving matter and energy, innovators have democratized information

By Naomi Oreskes and Erik M. Conway

Illustration by Tavis Coburn

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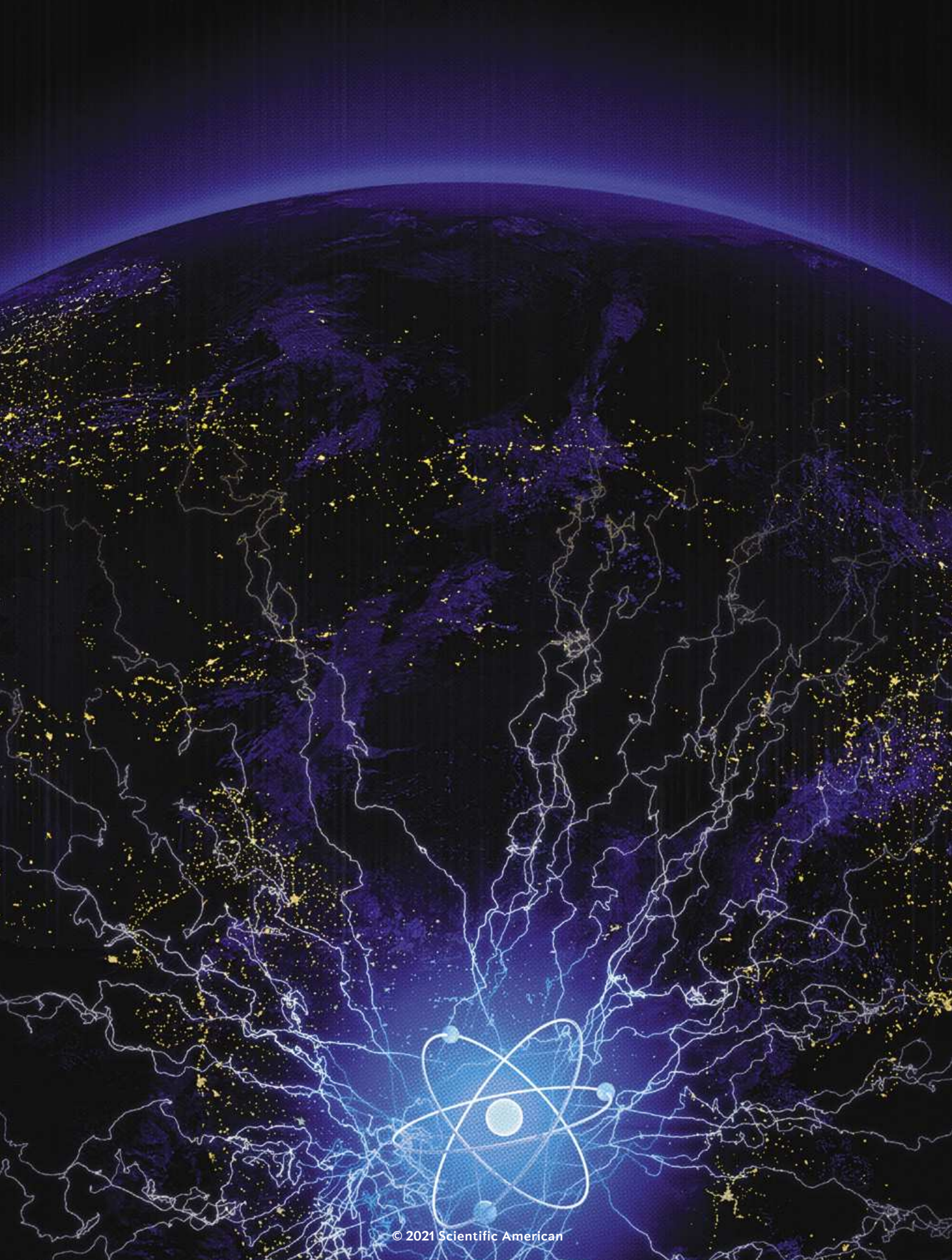

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IT IS A TRUISM AMONG SCIENTISTS THAT OUR ENTERPRISE BENEFITS HUMANITY because of the technological breakthroughs that follow in discovery's wake. And it is a truism among historians that the relation between science and technology is far more complex and much less linear than people often assume. Before the 19th century, invention and innovation emerged primarily from craft traditions among people who were not scientists and who were typically unaware of pertinent scientific developments. The magnetic compass, gunpowder, the printing press, the chronometer, the cotton gin, the steam engine and the water wheel are among the many examples. In the late 1800s matters changed: craft traditions were reconstructed as "technology" that bore an important relation to science, and scientists began to take a deeper interest in applying theories to practical problems. A good example of the latter is the steam boiler explosion commission, appointed by Congress to investigate such accidents and discussed in *Scientific American*'s issue of March 23, 1878.

Still, technologists frequently worked more in parallel with contemporary science than in sequence. Technologists—soon to be known as engineers—were a different community of people with different goals, values, expectations and methodologies. Their accomplishments could not be understood simply as applied science. Even in the early 20th century the often loose link between scientific knowledge and technological advance was surprising; for example, aviation took off before scientists had a working theory of lift. Scientists said that flight by machines "heavier than air" was impossible, but nonetheless airplanes flew.

When we look back on the past 200 years or so, the manipulation of matter and energy stands out as a central domain of both scientific and technical advances. Techno-scientific innovations have sometimes delivered on their promises and sometimes not. Of the biggest advances, three really did change our lives—probably for the better—whereas two were far less consequential than people thought they would be. And one of the overarching impacts we now recognize in hindsight was only weakly anticipated: that by moving matter and energy, we would end up moving information and ideas.

ONE STRONG EXAMPLE of science-based technology that changed our lives is electricity. Benjamin Franklin is famous for recognizing that lightning is an atmospheric electrical discharge and for demonstrating in the 1700s that lightning rods can protect people and property. But the major scientific advances in understanding electricity came later when Michael Faraday and James Clerk Maxwell established that it was the flow of electrons—matter—and that it could be understood in the broader context of electromagnetism. Faraday showed that electricity and magnetism are two sides of the same coin: moving electrons creates a magnetic field, and moving a magnet induces electric current in a conductor. This understanding, quantified in Maxwell's equations—a mathematical model for electricity, magnetism and light—laid the foundation for the invention of the dynamo, electricity generation for industries and households, and telecommunications: telegraph, telephone, radio and television.

Electricity dramatically expanded the size of factories. Most factories had been powered by water, which meant they had to be located close to streams, typically in narrow river valleys where space was tight. But with electricity, a factory could be erected anywhere and could take on any size, complete with lighting so it could run around the clock. This innovation broadened mass production and, with it, the growth of consumer society. Electricity also transformed daily life, powering the subways, streetcars and commuter rail that let workers stream in and cities sprawl out and creating the possibility of suburban living. Home lighting extended the time available for reading, sewing and other activities. Entertainment blossomed in a variety of forms, from the "electrifying" lighting displays of the 1904 St. Louis World's Fair to cinema and radio. Home electricity was soon also powering refrigerators, toasters, water heaters, washing machines and irons. In her 1983 prizewinning book *More Work for Mother,* Ruth Schwartz Cowan argues that these "labor-saving" appliances did more to raise expectations for

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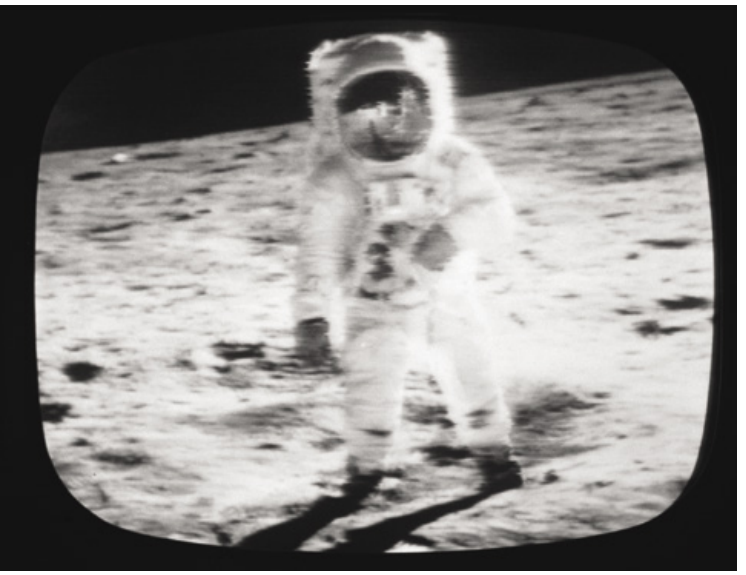

TELEVISION became widespread in time to deliver the moon landing in the summer of 1969.

household order and cleanliness than to save women labor, yet there is no question that they changed the way Americans lived.

One of the most significant and durable changes involved information and ideas. Electricity made the movie camera possible, which prompted the rise of cinema. The first public movie screening was in Paris, in 1895, using a device inspired by Thomas Edison's electric Kinetoscope. (The film showed factory workers leaving after a shift.) Within a few years a commercial film industry had developed in Europe and America. Today we think of movies primarily as entertainment—especially given the emergence of the entertainment industry and the centrality of Hollywood in American life—but in the early 20th century many (possibly most) films were documentaries and newsreels. The newsreels, a standard feature in cinemas, became a major source of information about world and national events. They were also a source of propaganda and disinformation, such as a late-1890s "fake news" film about the Dreyfus affair (a French political scandal in which a Jewish army officer was framed on spy charges laced with anti-Semitism) and fake film footage of the 1898 charge up San Juan Hill in the Spanish-American War.

Information drove the rise of radio and television. In the 1880s Heinrich Hertz demonstrated that radio waves were a form of electromagnetic radiation—as predicted by Maxwell's theory—and in the 1890s Indian physicist Jagadish Chandra Bose conducted an experiment in which he used microwaves to ignite gunpowder and ring a bell, proving that electromagnetic radiation could travel without wires. These scientific insights laid the foundations for modern telecommunications, and in 1899 Guglielmo Marconi sent the first wireless signals across the English Channel. Techno-fideists—people who place faith in technology—proclaimed that radio would lead to world peace because it enabled people across the globe to communicate. But it was a relatively long road from Marconi's signals to radio as we know it: the first programs were not developed until the 1920s. Meanwhile radio did nothing to prevent the 1914–1918 Great War, later renamed World War I.

In the early 20th century there was little demand for radio beyond the military and enthusiasts. To persuade people to buy radios, broadcasters had to create content, which required sponsors, which in turn contributed to the growth of advertising, mass marketing and consumer culture. Between the 1920s and the 1940s radios became a fixture in American homes as programs competed with and often replaced newspapers as people's primary source of information. Radio did not bring us world peace, but it did bring news, music, drama and presidential speeches into our lives.

Television's story was similar: content had to be created to move the technology into American homes. Commercial sponsors produced many early programs such as Texaco Star Theater and General Electric Theater. Networks also broadcast events such as baseball games, and in time they began to produce original content, particularly newscasts. Despite (or maybe because of) the mediocre quality of much of this programming, television became massively popular. Although its scientific foundation involved the movement of matter and energy, its technological expression was in the movement of information, entertainment and ideas.

World War II tore the world apart again, and science-based technologies were integral. Historians are nearly unanimous in the belief that operations research, code breaking, radar, sonar and the proximity fuse played larger roles in the Allied victory than the atomic bomb, but it was the bomb that got all the attention. U.S. Secretary of War Henry Stimson promoted the idea that the bomb had brought Japan to its knees, enabling the U.S. to avoid a costly land invasion and saving millions of American lives. We know now that this story was a postwar invention intended to stave off criticism of the bomb's use, which killed 200,000 civilians. U.S. leaders duly declared that the second half of the 20th century would be the Atomic Age. We would have atomic airplanes, trains, ships, even atomic cars. In 1958 Ford Motor Company built a model chassis for the Nucleon, which would be powered by steam from a microreactor. (Needless to say, it was never completed, but the model can be seen at the Henry Ford Museum in Dearborn, Mich.) Under President Dwight Eisenhower's Atoms for Peace plan, the U.S. would develop civilian nuclear power both for its own use and for helping developing nations around the globe. American homes would be powered by free nuclear power "too cheap to meter."

The promise of nuclear power was never fulfilled. The U.S. Navy built a fleet of nuclear-powered submarines and switched its aircraft carriers to nuclear power (though not the rest of the surface fleet), and the government assembled a nuclear-powered freighter as a demonstration. But even small reactors proved too expensive or too risky for nearly any civilian purpose. Encouraged by the U.S. government, electrical utilities in the 1950s and 1960s began to develop nuclear generating capacity. By 1979 some 72 reactors were operating across the country, mostly in the East and the Midwest. But even before the infamous accident at the Three Mile Island nuclear power plant that year, demand for new reactors was weakening because capital and construction costs were not falling and public opposition was rising. In the five years after the accident, more than 50

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reactors planned in the U.S. were canceled and others required costly retrofits. Nuclear anxieties worsened after the 1986 Chernobyl disaster in the former Soviet Union. Today the U.S. generates about 20 percent of its electricity from nuclear plants, which, though significant, is hardly what nuclear energy's 1950s boosters had predicted.

WHILE SOME PUNDITS claimed the 20th century was the Atomic Age, others insisted it was the Space Age. American children in midcentury grew up watching science-fiction TV programs centered on the dream of interplanetary and intergalactic journeys, reading comic books starring superheroes from other planets and listening to vinyl records with songs about the miracle of space travel. Their heroes were Alan Shepard, the first American in space, and John Glenn, the first American to orbit Earth. Some of their parents even made reservations for a flight to the moon promised by Pan American World Airways, and Stanley Kubrick featured airplane space flight in his 1968 film, *2001: A Space Odyssey*. The message was clear: by 2001 we would be routinely flying in outer space.

WORLD WIDE WEB blurred the line between producers and consumers of media, a shift with cultural and political consequences that are still unfolding.

The essential physics required for space travel had been known since the days of Galileo and Newton, and history is replete with visionaries who saw the potential in the laws of motion. What made the prospect real in the 20th century was the advent of rocketry. Robert Goddard is often called the "father of modern rocketry," but it was Germans, led by Nazi scientist Wernher von Braun, who built the world's first usable rocket: the V-2 missile. A parallel U.S. Army–funded rocket program at the Jet Propulsion Laboratory demonstrated its own large ballistic missile shortly after the war. The U.S. government's Operation Paperclip discreetly brought von Braun and his team to the states to accelerate the work, which, among other things, eventually led to NASA's Marshall Space Flight Center.

This expensive scientific and engineering effort, pushed by nationalism and federal funding, led to Americans' landing on the moon and returning home in 1969. But the work did not result in routine crewed missions, much less vacations. Despite continued enthusiasm and, recently, substantial private investment, space travel has been pretty much a bust. Yet the same rockets that could launch crewed vessels could propel artificial satellites into Earth orbit, which allowed huge changes in our ability to collect and move information. Satellite telecommunications now let us send information around the globe pretty much instantaneously and at extremely low cost. We can also study our planet from above, leading to significant advances in weather forecasts, understanding the climate, quantifying changes in ecosystems and human populations, analyzing water resources and—through GPS—letting us precisely locate and track people. The irony of space science is that its greatest payoff has been our ability to know in real time what is happening here on Earth. Like radio and TV, space has become a medium for moving information.

A SIMILAR EVOLUTION OCCURRED with computational technology. Computers were originally designed to replace people (typically women) who did laborious calculations, but today they are mainly a means to store, access and create "content." Computers appeared as a stealth technology that had far more impact than many of its pioneers envisaged. IBM president Thomas J. Watson is often cited as saying, in 1943, that "I think there is a world market for maybe five computers."

Mechanical and electromechanical calculation devices had been around for a long time, but during World War II, U.S. defense officials sought to make computation much faster through the use of electronics—at the time, thermionic valves, or vacuum tubes. One outcome was Whirlwind, a real-time tube-based computer developed at the Massachusetts Institute of Technology as a flight simulator for the U.S. Navy. During the cold war, the U.S. Air Force turned Whirlwind into the basis of an air-defense system. The Semi-Automatic Ground Environment system (SAGE) was a continent-scale network of computers, radars, wired and wireless telecommunications systems, and interceptors (piloted and not) that operated into the 1980s. SAGE was the key to IBM's abandoning mechanical tabulating machines for mainframe digital computers, and it revealed the potential of very large-scale, automated, networked management systems. Its domain, of course, was information—about a potential military attack.

Early mainframe computers were so huge they filled the better part of a room. They were expensive and ran very hot, requiring cooling. They seemed to be the kind of technology that only a government, or a very large business with deep pockets, could ever justify. In the 1980s the personal computer changed that outlook dramatically. Suddenly a computer was something any business and many individuals could buy and use not just for intense computation but also for managing information.

That potential exploded with the commercialization of the

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Internet. When the U.S. Defense Advanced Research Projects Agency set out to develop a secure, failure-tolerant digital communications network, it already had SAGE as a model. But SAGE, built on a telephone system using mechanical switching, was also a model of what the military did not want, because centralized switching centers were highly vulnerable to attack. For a communications system to be "survivable," it would have to have a set of centers, or nodes, interconnected in a network.

The solution—ARPANET—was developed in the 1960s by a diverse group of scientists and engineers funded by the U.S. government. In the 1980s it spawned what we know as the Internet. The Internet, and its killer app the World Wide Web, brought the massive amount of information now at our fingertips, information that has changed the way we live and work and that has powered entirely new industries such as social media, downloadable entertainment, virtual meetings, online shopping and dating, ride sharing, and more. In one sense, the history of the Internet is the opposite of electricity's: the private sector developed electrical generation, but it took the government to distribute the product widely. In contrast, the government developed the Internet, but the private sector delivered it into our homes—a reminder that casual generalizations about technology development are prone to be false. It is also well to remember that around a quarter of American adults still do not have high-speed Internet service.

WHY IS IT THAT ELECTRICITY, telecommunications and computing were so successful, but nuclear power and human space travel have been a letdown? It is clear today that the latter involved heavy doses of wishful thinking. Space travel was imbricated with science fiction, with dreams of heroic courage that continue to fuel unscientific fantasies. Although it turned out to be fairly manageable to launch rockets and send satellites into orbit, putting humans in space—particularly for an extended period—has remained dangerous and expensive.

NASA's space shuttle was supposed to usher in an era of cheap, even profitable, human spaceflight. It did not. So far no one has created a gainful business based on the concept. The launch in late May 2020 of two astronauts to the International Space Station by SpaceX may have changed the possibilities, but it is too soon to tell. Most space entrepreneurs see tourism as the route to profitability, with suborbital flights or perhaps floating space hotels for zero-*g* recreation. Maybe one day we will have them, but it is worth noting that in the past tourism has followed commercial development and settlement, not the other way around.

Nuclear power also turned out to be extremely expensive, for the same reason: it costs a lot to keep people safe. The idea of electricity too cheap to meter never really made sense; that statement was based on the idea that tiny amounts of cheap uranium fuel could yield a large amount of power, but the fuel is the least of nuclear power's expenses. The main costs are construction, materials and labor, which for nuclear plants have remained far higher than for other power sources, mainly because of all the extra effort that has to go into ensuring safety.

Risk is often a controlling factor for technology. Space travel and nuclear power involve risk levels that have proved acceptable in military contexts but mostly not in civilian ones. And despite the claims of some folks in Silicon Valley, venture capitalists generally do not care much for risk. Governments, especially when defending themselves from actual or anticipated enemies, have been more entrepreneurial than most entrepreneurs. Also, neither human space travel nor nuclear power was a response to market demand. Both were the babies of governments that wanted these technologies for military, political or ideological reasons. We might be tempted to conclude, therefore, that the government should stay out of the technology business, but the Internet was not devised in response to market demand either. It was financed and developed by the U.S. government for military purposes. Once it was opened to civilian use, it grew, metamorphosed and, in time, changed our lives.

In fact, government played a role in the success of all the technologies we have considered here. Although the private sector brought electricity to the big cities—New York, Chicago, St. Louis—the federal government's Rural Electrification Administration brought electricity to much of America, helping to make radio, electric appliances, television and telecommunications part of everyone's daily lives. A good deal of private investment created these technologies, but the transformations that they wrought were enabled by the "hidden hand" of government, and citizens often experienced their value in unanticipated ways.

THESE UNEXPECTED BENEFITS seem to confirm the famous saying—variously attributed to Niels Bohr, Mark Twain and Yogi Berra—that prediction is very difficult, especially about the future. Historians are loath to make prognostications because in our work we see how generalizations often do not stand up to scrutiny, how no two situations are ever quite the same and how people's past expectations have so often been confounded.

That said, one change that is already underway in the movement of information is the blurring of boundaries between consumers and producers. In the past the flow of information was almost entirely one-way, from the newspaper, radio or television to the reader, listener or viewer. Today that flow is increasingly two-way—which was one of Tim Berners-Lee's primary goals when he created the World Wide Web in 1990. We "consumers" can reach one another via Skype, Zoom and FaceTime; post information through Instagram, Facebook and Snapchat; and use software to publish our own books, music and videos—without leaving our couches.

For better or worse, we can expect further blurring of many conventional boundaries—between work and home, between "amateurs" and professionals, and between public and private. We will not vacation on Mars anytime soon, but we might have Webcams there showing us Martian sunsets. SA

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THE WORST TIMES ON EARTH

Mass extinctions send us a warning about the future of life on this planet

By Peter Brannen

Illustration by Pascal Blanchet

PANGAEA, 252 MILLION YEARS AGO—THE WORLD IS OVER. SIBERIA HAS been erupting for 300,000 years, is still erupting and won't stop. Not a volcano, mind you, but Siberia—two million square miles of it. A suppurating, billowing, continent-scaled wasteland of glowing rock and steam. The seas, once resplendent with horn corals and sponge reefs, are now sour and laden with mercury. Hot as soup, they bubble deathly swamp gas that feeds vile, hurricane-churned slicks of slime. The seabed is vacant, as scuttling trilobites die out after a quarter of a billion years. Beside this rancid ocean, on the shores of a blasted supercontinent, the forests are gone. Instead hot rivers now spill over the dead land in wide braids. Fungus blooms where vanished groves of ferns once held contests full of fangs and armor—gorgonopsids battling pareiasaurs. Their final bones are now scoured by hot winds and bleached by a searing sunlight, unfiltered by ozone. Night falls and brings odd constellations that light the dead waves, lapping at dead shores, tossing old bits of a dead reef from a dead sea. It smells awful. The planet is ruin and slime and heat. The ocean suffocates. Bacterial mounds spread.

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A hundred thousand suns rise and fall on a hopeless world. A hundred thousand springtimes arrive with no respite. It's still all but barren. A million years of misery pass. Ten million.

At long last, the planet is finally reborn—this time with dinosaurs and ichthyosaurs and pterosaurs and mammals and turtles and sturgeon—almost as if a new story entirely has begun, exuberant, confident, vital: the Mesozoic era. The old story, too dark to retell, has long been filed away somewhere deep in the great cabinets of Earth, along with an epitaph in the rocks, written in geochemistry: carbon dioxide destroyed this world.

MASS EXTINCTIONS are not merely bad days in Earth history. They are not even very bad days. They are the very, very worst days in the entire half-billion-year history of complex life. They are supremely horrifying, astronomically rare, global Ragnaroks that end the lineages of most living creatures on the planet. They are terrible, surreal things: 20,000 years of suffocating greenhouse heat punctuated by volcanic winter blasts or an afternoon of celestial terror and tsunamis. And until around 1980, they were mostly thought to be disreputable speculation.

Over the past two centuries the field of geology, like the fossil record itself, has been characterized by long periods of stasis punctuated by exhilarating moments of upheaval and innovation. It would be arbitrary to identify *one* founding figure for the modern study of geology, but one could do worse than Scottish geologist James Hutton, who did much to reveal the "abyss of time" underneath us. At a salt-sprayed Siccar Point on the eastern coast of Scotland in 1788, he spied an outcrop made of two kinds of rock, one stacked on top of the other, meeting abruptly in the middle. But the rock on the bottom—laminations of deep-sea muck—had been formed at the bottom of the ocean, tilted sideways, thrust up into the air and planed off by wind and erosion. And the rock on the top had been formed by tropical rivers on dry land. The missing time implied between the two rocks, now conjoined but separated by an unthinkable gap, shattered Hutton. The body of his writing is notoriously obtuse and unimpressive; he apparently saved all his eloquence for one haunting observation that, in the confusion of Earth beneath our feet, "we find no vestige of a beginning, no prospect of an end." Although the history of humanity has played out in the shallows so far, time, it turns out, is *deep*.

Geologists cast off the strictures of biblical time and Noah's flood, and their new field matured over the decades, spurred by a significant material reward for finding coal and minerals in a strange new industrial age. The story of life on Earth, however fragmentary and tantalizing, slowly revealed itself.

At this magazine's founding in the mid-1800s, the field was in its adolescence. It was still dominated by men of means—the kind of ascotted dilettantes rendered humorlessly in oil and lithograph portraits. The contributions of women such as Mary Anning, the unmatched fossil hunter who scoured the English shoreline unearthing the local "snakestones" and "stone crocodiles" that littered the wave-battered Jurassic Coast, were acknowledged only sheepishly. Although *Scientific American* headlines from the time still hint at a somewhat rudimentary state of affairs ("Experts Doubt the Sun Is Actually Burning Coal"), by midcentury geology had nonetheless been established as an empirical, systematized field of inquiry with roots in antiquity—one of the many such intellectual eddies that swirled out of Enlightenment-era "natural philosophy." That is, it now had rules. The rules were deceptively simple and powerful. Layers of ocean rock now propped up at unusual angles on land must have once laid flat on a seafloor in some distant age. Dikes of old magma that pierced this stony tiramisu must have worked their shoots into the layered rock sometime after. The fossils entombed in these rock layers could be correlated to those fossils and those rocks with the same layers, way over there.

In 1860 English geologist John Phillips drew on the fossil-collecting labor of decades prior, and a growing body of paleontology literature scattered across elegant monographs, to plot a surprisingly modern curve of the richness of life over Earth history, the first ever such diagram. The graph ominously included two profound dips in life: one crash that separated the trilobite-spangled Paleozoic era from the dinosaur-haunted Mesozoic era and another plunge that separated the Mesozoic from our own Cenozoic time (all terms of Phillips's invention). The dramatic breaks in fossil life hinted at some kind of ancient calamity that divided the great ages and supported the blasphemous idea that species—that is, God's very Creation—might go extinct, which had been proposed half a century earlier by the renowned French naturalist Georges Cuvier. On considering the odd elephant bones that littered the New World, of mammoths and mastodons ("*animal de l'Ohio*"), Cuvier had proposed that life on Earth, like French rule, could be swept away in "revolutions." Phillips's graph provided something close to quantitative proof, and Phillips himself thought that each recovery consisted of separate acts of divine creation. Yet it would take more than a century for anyone to take the idea of mass extinctions seriously again.

This is because, by the end of the 19th century, the field was still dominated, and would continue to be dominated for decades, by the enduring framework of "uniformitarianism." This concept, popularized by Charles Lyell, is summarized in a catchphrase still taught to geology students: "The present is the key to the past." That is, the unhurried processes at work on the face of Earth today—the relentless if unimpressive work of rain on rock, the inexorable incision of rivers into highlands or the piling of sand into desert dunes—have always been plying the planet in the same tedious fashion and could account for everything we find in the rock record. Painting on this vast new canvas of time, Charles Darwin would propose that similarly small but steady biological changes over generations, filtered by the relentless tournament of life and death, and given Hutton's eons to ramify, could produce the "endless forms" of life "most beautiful" on Earth today. Pointedly absent from this measured account of planetary history were the gauche cataclysms of Cuvier and Phillips.

GEOLOGY WAS UPENDED in the middle of the 20th century by the plate tectonic revolution—the validation of the once fringe idea that continents drifted across the world like rudderless ships. Even so, the idea of sudden apocalyptic global mass extinctions remained suspect at best. Catastrophism was spooky, reminiscent of a benighted prescientific world where capricious gods subjected the world to cleansing acts of global destruction. Worse, speculation about why the dinosaurs had disappeared had become something of a cottage industry among cranks, and serious scientists were nervous about associating with a crowd who proposed, among dozens of other incoherent ideas for their demise, "dwindling brain and consequent stupidity," development of heads that became

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"too heavy to lift," "psychotic suicidal factors," "competition with caterpillars," "terminal hay fever" and "methane poisoning from dinosaur flatulence." And yet the orthodoxy began to crack.

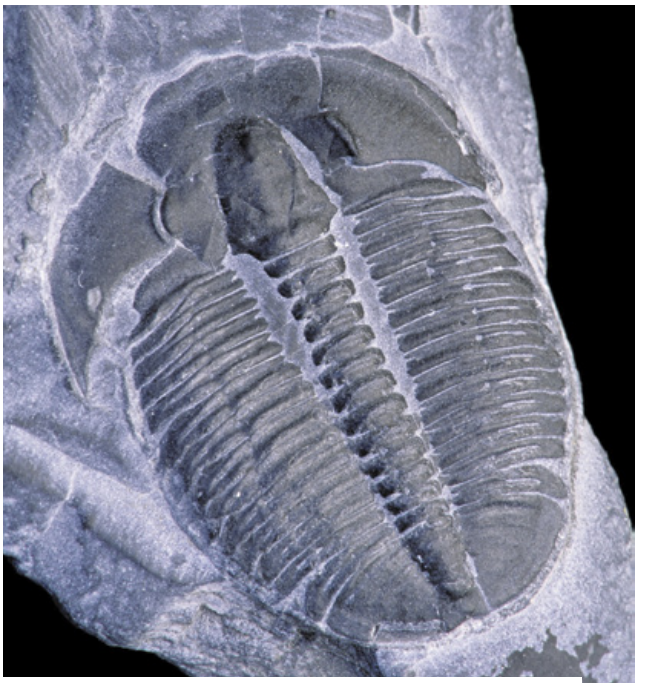
"*Neokatastrophismus?*" the iconoclastic German scientist Otto Schindewolf asked of his fellow paleontologists in 1963, attempting to revive Cuvier's catastrophism for the 20th century. Because his question was posed in German, few English-speaking scientists felt the need to reply. But Schindewolf could no longer overlook the ominous interruption of life he saw—among other places—exposed in the ancient rocks of the Salt Range in Pakistan. There appeared to be a dreadful global collapse of the ocean ecosystem at the end of the Permian period a quarter of a billion years ago (in fact, the greatest mass extinction in Earth history), just as Phillips had plotted more than a century prior. Schindewolf conscripted a supernova for his vision of the apocalypse, proposing that it might have irradiated Earth and seeded the biosphere with ruinous mutations.

In that same year American Norman Newell, plotting the fates of 2,500 animal families over Earth history, noted six intervals when extinction seemed to cut a broad swath through all of life, instead proposing dramatic sea-level changes as his preferred Grim Reaper. And at the end of the decade Digby McLaren, director of the Canadian Geological Survey's Institute of Sedimentary and Petroleum Geology, insisted in his 1969 presidential address to the Paleontological Society that his fellow paleontologists were trying to "define out of existence" the obvious breaks in the fossil record, such as a devastating wave of death 375 million years ago that wiped out the largest global reef system in the history of life. "I cannot accept a uniformitarian explanation," he said of the catastrophe, glaringly apparent in ancient rocks from Iran to Alberta. McLaren had an idea for what could cause such a discontinuity.

"I shall, therefore, land a large or very large meteorite in the Paleozoic Pacific," he announced, capable of generating "a wave twenty thousand feet high. This will do." McLaren's address, it is reported, was "met with embarrassed silence," and many paleontologists in the audience, still under Lyell's spell, assumed he must have been joking.

Then, in 1980, an asteroid landed in the field. Walter Alvarez, then a young University of California, Berkeley, professor, was traipsing the Apennines above the medieval Italian town of Gubbio. In this mountainous pile of ancient limestone seafloor, pushed up by the grinding advance of Africa into Europe, there was a sharp break—a lifeless clay layer—between the placid sea life of dinosaur times and the impoverished life of the early age of mammals. Perhaps this transformative interval took place over millions of years, validating the uniformitarian view. Or perhaps Cuvier and Phillips had it right all along, and the turnover was devastatingly short. Curious, Alvarez recruited his father, Luis, a Nobel-winning physicist, to help tackle the question. It was quite the second act for the elder Alvarez, a pioneer of military radar technology and Manhattan Project alum who helped to develop the atomic bomb and even watched "Little Boy" explode over Hiroshima from an attending B-29. His wartime work became unexpectedly relevant to the catastrophe they were investigating, which throttled the planet some 66 million years earlier.

The Alvarezes knew that unusual elements like iridium were delivered to Earth from above by an eternal drizzle of space dust, at a steady rate. Measure the iridium in the ominous clay layer, they reasoned, and if there's just a little bit, the dramatic turnover in life couldn't have taken very long. Conversely, if there's a lot of iridium, it took a very long time indeed. But what if, as they discovered, there was 100 times more iridium than they ever expected? After bombarding the clay samples with neutrons from a nuclear reactor and analyzing them, the Alvarezes were astonished. The only vehicle large enough for this much exotic material was not a light drizzle of space dust but one truly gigantic space rock. (Often omitted in this account, though not by the Alvarezes themselves, is the fact that Dutch geologist Jan Smit and Belgian geologist Jan Hertogen made the very same discovery among ancient ocean rocks in Spain at the very same time and even published their results in the journal *Nature* two weeks earlier than the Alvarezes' landmark *Science* paper.)



TRILOBITES swam the seas for a quarter of a billion years before being annihilated in history's worst mass extinction.

Ed Reschke *Getty Images*

The resulting chaos from such an impact would be like all-out nuclear warfare, only worse. There would be the unimaginable heat from the initial explosion, which would have been thousands of times more powerful than the detonation of all the nuclear weapons on Earth at the height of the cold war, all in one place, all at once. "Certainly enough," as one impact modeler put it to me, "to lift a mountain back into space at escape velocity." It has been proposed that as this spacebound ejecta encircled the globe, it might have turned the atmosphere into a pizza oven for 20 minutes (with dinosaurs playing the role of pepperoni). Then there might have been the decades of darkness and cold from the nuclear winter to follow, starving any lingering creature lucky enough to have avoided being evaporated outright by the asteroid, swept up in its tsunamis, or turned to charcoal by the ballistic reentry of its debris into the atmosphere.

In 1991 whatever lingering skepticism about the impact that remained among uniformitarian hardliners was wiped away by the discovery of a 110-mile crater buried under tens of millions of years of limestone on Mexico's Yucatán peninsula. In fact, the

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1867 RENDERING of a woolly mammoth, whose bones led Georges Cuvier to propose that life could be extinguished in "revolutions."

crater had already been discovered in 1978 by geophysicists working for the Mexican national oil company Pemex, but they had announced their findings at a geophysics conference that had escaped notice of paleontologists for more than a decade. And the structure had been found some 1,000 years earlier by the Maya, who built settlements around limestone sinkholes that pock the Yucatán and that provided freshwater. The pattern of these sinkholes reflects the deeply disturbed rock far below and maps almost exactly onto the crater's edge, in a 110-mile ring.

Popular culture took note. The 1990s saw a rash of impact-inspired cable specials and movies strewn with bad CGI, which—along with the astounding, apocalypse-scaled collision of Comet Shoemaker-Levy 9 with Jupiter in 1994—were sufficient to convince the public of the dangers of space rocks. This is typically where the story ends. As far as most people are concerned, mass extinctions are what happen when big things fall out of the sky.

BUT SOMETHING FUNNY HAPPENED over the next 30 years as geologists fanned out across the globe to look for convincing evidence of impacts—such as layers of iridium, shocked quartz or giant craters—at the ominous rock boundaries that mark the four other major mass extinctions in Earth history. They didn't find any. And all but one of the so-called Big Five mass extinctions were *even more severe* than the catastrophe that wiped out the nonbird dinosaurs.

In fact, there even existed major impact structures, such as the Triassic-age 62-mile-wide Manicouagan Crater in Quebec (now a circular system of lakes amid a boreal paradise of blackflies) or the massive crater that created the Chesapeake Bay 36 million years ago, that did not seem to bother life much at all. Given the remarkable correlation of the Yucatán impact with the disappearance of the large dinosaurs (and much of the rest of life on Earth at the end of the Cretaceous period), this came as a surprise. Stranger still, the stunning finale of the age of dinosaurs was also accompanied not only by an envoy from outer space but by one of the largest volcanic events in the history of animal life: a swath of eruptions that drowned much of India *miles* deep in lava. While the consensus is that the asteroid did most of the damage, this was the same class of world-changing eruptions responsible not only for dozens of minor mass extinctions and climate misadventures throughout Earth history but several of the other major mass extinctions as well, including the worst ever at the end of the Permian 252 million years ago.

In the past few decades a subtler story about mass extinctions has emerged. Geologists are now armed with powerful techniques Hutton couldn't have dreamed of. Scattering to remote rock outcrops around the world or to archives of muck hoisted from the bottom of the ocean by drill ships, they wring secrets out of old seashells with mass spectrometers, and from age-battered hunks of granite with radioisotope geochronology, and from fossil and geochemical databases with neural networks underwritten by blistering processing power. And in this diffuse project to understand Earth history, geologists have in recent years revealed a roster of existential threats to life far more intimate than simply death from above. The most frequent mass killer of life on Earth, it turns out, is Earth itself. And the most reliable murder weapon is carbon dioxide.

One hundred and thirty-five million years before a mindless hunk of space garbage intercepted Earth's orbit and ruined a per-

Alamy

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EXPOSED SEAM in Colorado of the K-T boundary, which marks the mass extinction that ended the reign of the dinosaurs.

Julie Mowbray *Alamy*

fectly good dinosaur world, the planet was gripped by a mass extinction that was even worse. A world of bizarre crocodilians, giant amphibians, stony corals, a ubiquity of strange but venerable eel-like creatures, and 80 percent of the rest of complex life on Earth was destroyed. As the supercontinent Pangaea pulled apart at the seams, stretching like taffy, an open sore of oozing, incandescent rock erupted at the surface, covering three million square miles in lava in pulses over 600,000 years. While the eruptions would have caused all sorts of chaos, perhaps most important they injected thousands of gigatons of carbon dioxide into the atmosphere, and the oceans overdosed on this volcanic CO_2. The seawater acidified as a simple matter of chemistry, and the temperature of the planet soared as a simple matter of physics. This is what CO_2 does. Today the New Jersey Palisades across the Hudson River from New York City are the volcanic plumbing that remains from these titanic eruptions of the Triassic end times, old magma that is matched by the same volcanic rock, of the same age, as far afield as Morocco, Brazil, Nova Scotia and Spain.

Hundreds of millions of years earlier the two oldest major mass extinctions destroyed planets we wouldn't recognize, their continents misshapen and scattered about unfamiliar oceans. The oceans of these alien planets were patrolled by gigantic cephalopods and, later, even more gigantic fish, guillotine-mawed and fortified by helmets of bone. Our planet endlessly cycles carbon—the stuff of life—through rocks, air, water and life in a balance that keeps the climate habitable and ocean chemistry hospitable. But these archaic worlds saw this carbon cycle suddenly derailed—unraveled by CO_2-sucking episodes of tropical mountain building, accelerated rock weathering and the novel global geoengineering project of land plants. These kill mechanisms are somewhat more convoluted, and admittedly less dramatic, than an asteroid, but they did the trick. These bygone planets spun out of control, alternately freezing and broiling as Earth struggled to regain its composure and wrangle a global carbon cycle gone haywire.

But it was 252 million years ago, on the forsaken planet that opened this tour of ancient apocalypses—that sun-bleached world, with oceans almost absent of animals—when the story of life on Earth nearly came to its premature conclusion. This was Pangaea, a world before dinosaurs or mammals or flowers. But it was still a rich world, one with conifers and lithe, vaguely leonine predators and lumbering, warty, reptile prey. And then, it was over. It ended in a continent-scaled flood of glowing rock, brief volcanic winters issuing from the eruptions and a roster of billowing volcanic gases, many of which would be banned on a battlefield—such as chlorine gas and mercury.

As the magma incinerated underground seams of salt and gypsum, eruptions of halocarbons would have obliterated the ozone layer—and indeed, plant fossils bear the mutations wrought by this ancient atmospheric destruction. But it wasn't until the seams of magma feeding these eruptions hit huge deposits of natural gas, coal and carbon-rich rocks underground that the greatest mass extinction ever hit its appalling crescendo. Methane and carbon dioxide exploded out of the ground by the tens of thousands of gigatons. Temperatures spiked by almost 22 degrees Fahrenheit. And in the oceans, where spreading anoxia and acidification wiped out 96 percent of life, it was as hot as a jacuzzi. And then, in the fossil record, silence.

AT THE START of the industrial revolution, long slumbering forests of carbon were resurrected from the ancient Earth and pressed into service in the furnaces of modernity. We know that this artificial fire can't go on forever without immiserating our world. At 416 parts per million, carbon dioxide is already higher than it has been in millions of years and is perhaps rising even faster than in these greatest calamities of all time. Meanwhile centuries—millennia even—of hunting, land clearing and pollution have impoverished the natural world. By one estimate, at the rate at which we are currently driving species extinct, we could match the biological devastation of those towering mass extinctions of the ancient past within 300 to 12,000 years. This might sound like a long time frame, but from a geologic perspective, it is downright subliminal. More worryingly, there may yet exist unseen ecological cliff edges along the way, beyond which the biosphere does not simply suffer the onslaught of attrition but collapses suddenly in cascading failures. In other words, there may be tipping points—points of no return.

We know what we have to do to avoid being inducted into the wretched Pantheon of the worst things that have ever happened in Earth history. We must set aside swaths of the planet—in the form of marine protected areas, natural reserves and corridors for migration—to allow the living world to recover from the uppercut we have already delivered it. Then, we must simply stop digging up old life from deep in Earth's crust and lighting it on fire at the surface. As humanity leans on the very same levers pulled in the very worst things that have ever happened in history, we must consult the ages and listen to the counsel of broken worlds past. SA

Peter Brannen is a science journalist whose book *The Ends of the World* is about the five major mass extinctions (Ecco, 2017). Brannen was a 2018–2019 Scripps Fellow at the University of Colorado Boulder.

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A HISTORY IN LAYERS

What mark will we leave on the planet?

By Jan Zalasiewicz

Photograph by Andrew Myers

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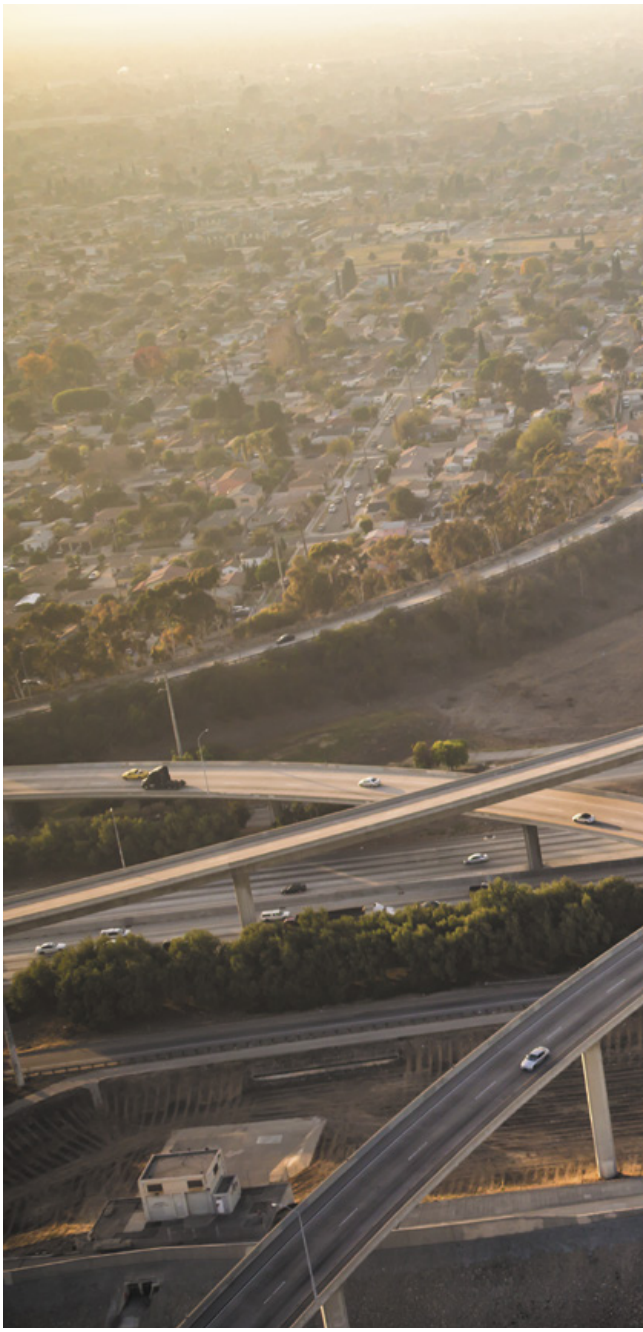
THE IDEA WAS BORN IN MEXICO, IN THE YEAR 2000. It was pure improvisation by Paul Crutzen, one of the world's most respected scientists. The Dutch scholar was widely known for arguing that all-out atomic war would trigger a "nuclear winter" lethal to plant and animal life across the planet, and he had won a Nobel Prize for research into another global threat: human-caused destruction of Earth's ozone layer.



In Mexico he was listening to experts discuss evidence for changes in the global environment that had occurred throughout the Holocene, a distinct epoch that geologists say began 11,700 years ago and continues today. Growing visibly more frustrated, he burst out: "No! We are no longer in the Holocene. We are in"—he paused to think—"the Anthropocene!"

The room went silent. The term had apparently hit home. And it kept coming up, again and again, for the rest of the meeting. That year Crutzen co-wrote an article with Eugene Stoermer (since deceased), a specialist in microscopic algae called diatoms who had independently coined the term "Anthropocene" some years earlier. The evidence, the two men said in the article, was clear: industrialized humanity had changed the composition of Earth's atmosphere and oceans and had modified the landscape and biosphere—including diatom populations. We were living on a new, human-driven Earth quite different from the old one. Spurred by Crutzen's prestige and vivid, persuasive writing, the concept spread rapidly among the thousands of scientists in the International Geosphere-Biosphere Program, which had sponsored the Mexico meeting. "The Anthropocene" began to appear in scientific papers around the world.

But was this really *geologic* change—change so profound that its signals are imprinted into geologic strata across the planet? Could humans really wreak change as dramatic as the transformations that started the Holocene 11,700 years ago, when extensive glaciers covering much of Earth were retreating, melting so much they raised sea level globally by 120 meters? Were human influences on the dirt beneath our feet as significant as when the Pleistocene epoch began, 2.6 million years ago, as the Ice Age tightened its grip? Could human effects only a few centuries old truly be measured alongside the great shifts of our planet's tumultuous geologic past, where time units are measured in millions—and even billions—of years?

The idea had appeared before. In the 19th and early 20th centuries scholars such as Italian cleric Antonio Stoppani and American naturalist Joseph LeConte floated terms such as Anthropozoic and Psychozoic, but geologists were dismissive, even scathing. How could human activity—no matter how impressive—compare with profound changes such as the creation and destruction of entire oceans and mountain ranges, massive volcanic eruptions and monstrous collisions

Prop styling by **Angela Campos** *Stockland Martel (page 68)*; **Getty Images** *(this page)*

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HUMANS are paving paradise, transforming the planet's strata and defining a new geologic epoch: the Anthropocene.

by incoming meteorites? Against such a scale, human actions appeared fleeting and ephemeral.

There was another problem, too. Geologic terms such as Jurassic, Cretaceous, Pleistocene and Holocene are not just labels. They are formal names that are part of a complex geologic timescale that fundamentally characterizes how Earth evolved, thrived and struggled over 4.6 billion years. The names were accepted only after decades of evidence gathering and discussion by the International Commission on Stratigraphy. "Epochs" and the "eras" they belong to have specific technical meanings, and geologists take them seriously. Declaring a new epoch would imply that scientists believe humans are altering the course of the planet's evolution.

The Anthropocene had gone through none of the usual assessments. And esteemed as Crutzen is, he was an atmospheric chemist working on environmental stresses, not a geologist who was an expert in rock strata. Yet by 2008 members of the Stratigraphy Commission of the Geological Society of London realized that the term was increasingly being used in the literature as if it *were* a formal epoch. The society decided it had to confront the trend.

This cautious and conservative group meets in the old-world Council Room in London's Burlington House, complete with solemn portraits on the walls, where Victorian giants of the sciences such as Charles Darwin once walked. In this heavily traditional setting,

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MOUNTAINS of plastics in Jakarta and of concrete in New York City will persist long enough to permanently mark Earth's crust.

the scientists began the geologic assessment of the Anthropocene. Perhaps to their own surprise, most of them agreed that the term "had merit" as a potentially formal unit of the proper geologic timescale and should be examined. Geologist Philip Gibbard, who also chaired the International Commission on Stratigraphy's Subcommission on Quaternary Stratigraphy—which has power over the geologic timescale—proposed a working group that has been exploring the question ever since.

To make a case, scientists must show that human impacts will leave a clear mark, fossilized in strata, that could be readily recognized tens or hundreds of millions of years from now by some geologist in the far future. The focus on strata is important. To a geologist, geologic strata equal geologic time. The key is a "time-rock" interval—a layer of strata that can be hammered, sampled or dug in (as for dinosaur bones) and that defines a new course of history. For the Anthropocene epoch to have such deep geologic meaning and to have any chance of being made formal, it must show its own time-rock unit. Is there enough evidence to pass muster? One could make a good case.

ROCKS AND 'OIDS

LET'S START WITH MINERALS, the fundamental components of rocks. Metals, for example, are almost always bound up in various oxides, carbonates and silicates (with rare exceptions such as gold). Humans have learned to separate metals out of these compounds in huge quantities. We have manufactured more than 500 million metric tons of aluminum since World War II, enough to coat the entire U.S. in kitchen foil. As we scatter billions of cans, appliances, cigarette pack liners and other refuse across the landscape and into landfills, pure aluminum is becoming part of modern sediment layers.

The last great rise in mineral forms occurred about 2.5 billion years ago, when Earth's atmosphere became oxygenated. The event produced an array of oxides and hydroxides, including rust—which, incidentally, changed the color of the landscape from gray to red. But humans have now created another great rise by synthesizing many mineral compounds, such as tungsten carbide, common in tools and ballpoint pens. Perhaps the most striking inventions are "mineraloids" such as glasses and plastics. Before WWII plastics were limited to a few products such as shellac, Bakelite and rayon, but after the war they rocketed to the 300 million metric tons now made annually—roughly equivalent to the total human body mass. The qualities we find so useful in plastics—durability and resistance to decay—mean that they persist in the environment for many years.

The signature of plastic litter in the ground is strong enough, but it is even more geologically significant in the oceans. Because many sea creatures eat plastics, much of it ends up in the muds of the seafloor when the animals die—a first step to fossilization. Invisible to our eyes but more pervasive still are microplastics, such as the fibers detached from synthetic clothes. Even on remote ocean floors, far from land, researchers are finding thousands of fibers in every square meter of mud.

Human-made rocks are everywhere, too. For sheer bulk, concrete now reigns supreme; we have manufactured something like half a trillion metric tons to date. That is about a kilogram of concrete for every square meter of Earth's surface. Concrete forms the superstructures of our buildings, roads and dams, and broken-up fragments are now common in the turned-over ground underneath our towns and cities. It is already a signature rock of the Anthropocene, together with human-made bricks and ceramics. The enormous masses of the rocks we make impregnate the top part of Earth's crust, which we are also redistributing as big

Ulet Ifansasti *Getty Images*

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George Hammerstein *Getty Images*

machines dig and plow soil to construct buildings and grow food. Humans now shift more sediment than natural forces such as rivers and wind do.

CHEMICAL FINGERPRINTS

IN THE PAST CENTURY or so the burning of fossil fuels has largely powered the accelerated production and planetary deposition of new strata materials such as aluminum, plastic and concrete. The by-products of combustion are themselves so voluminous that they, too, leave a variety of chemical signals in sediments worldwide. The rise of carbon dioxide in the atmosphere since the industrial revolution began is about 100 times faster than the rate of rise when the glaciers retreated at the start of the Holocene. The emissions are captured and recorded in bubbles of air trapped in layer on layer of snow and ice frozen in the world's polar caps.

Combustion also produces smoke—incompletely burned particles that are tiny and inert. Falling to the ground worldwide, they form a geologically lasting smoke signal. The fires ignited by the meteorite impact that defines the boundary between the Cretaceous and Tertiary intervals left a similar trace in the rocks. The carbon from burned fossil fuels is also distinctly rich in the light carbon 12 isotope (^{12}C), which plants and animals readily absorb. As these life-forms die, they will be fossilized, leaving a permanent ^{12}C mark of the Anthropocene.

Widespread agriculture is casting its own chemical shadow. Humankind started farming about 10,000 years ago, but only since the early 1900s have farmers applied vast quantities of nitrogen fertilizer, extracted from the air by a technique known as the Haber-Bosch process, together with phosphorus dug from the ground. The enormous perturbations in soil, water and air leave clear chemical signatures. Lakes at high latitudes become polluted by these compounds, blown in by winds from distant farming regions. Fertilizer runoff from farm fields into streams and rivers and out to the sea overstimulates plankton production; as the huge blooms die and decay, they create "dead zones" that now suffocate seafloor life over hundreds of thousands of square kilometers every year. The devastated marine biology will tell its story as fossils in future strata.

Other chemical signals include persistent organic pollutants such as insecticides and toxic industrial chemicals such as dioxins, which now contaminate many sediments. Some of these may persist over geologic timescales, as did the long-chain carbon compounds produced by some ancient algae that paleontologists now use as tracers of climate tens of millions of years ago.

Tiny radioactive particles that spread around the globe after every nuclear bomb explosion are also detectable. In addition to the two such bombs dropped as part of war, various countries detonated more than 500 test bombs in the atmosphere between the mid-1940s and the late 1990s. The particles fell into soil, polar ice and seafloor sediment alike, and they were absorbed by animals and plants at the surface. This radioactive layer is one of the most abrupt Anthropocene signatures.

FOSSIL TRANSITIONS

WE HUMANS have obviously left our mark on the biological landscape as well. In particular, our species—a very minor player amid the planet's biota even a few thousand years ago—is now the dominant predator on land and sea. We appropriate roughly a quarter of Earth's total biological production for our needs. As a result, we make up about a third of the mass of all land vertebrates (based simply on body weight), and

DOES HUMANITY HAVE A FUTURE BEYOND EARTH?

"I think it's a dangerous delusion to envisage mass emigration from Earth. There's nowhere else in the solar system that's as comfortable as even the top of Everest or the South Pole. We must address the world's problems here. Nevertheless, I'd guess that by the next century, there will be groups of privately funded adventurers living on Mars and thereafter perhaps elsewhere in the solar system.

"We should surely wish these pioneer settlers good luck in using all the cyborg techniques and biotech to adapt to alien environments. Within a few centuries they will have become a new species: the posthuman era will have begun. Travel beyond the solar system is an enterprise for posthumans—organic or inorganic."

Martin Rees
British cosmologist and astrophysicist

Portrait by Kyle Hilton

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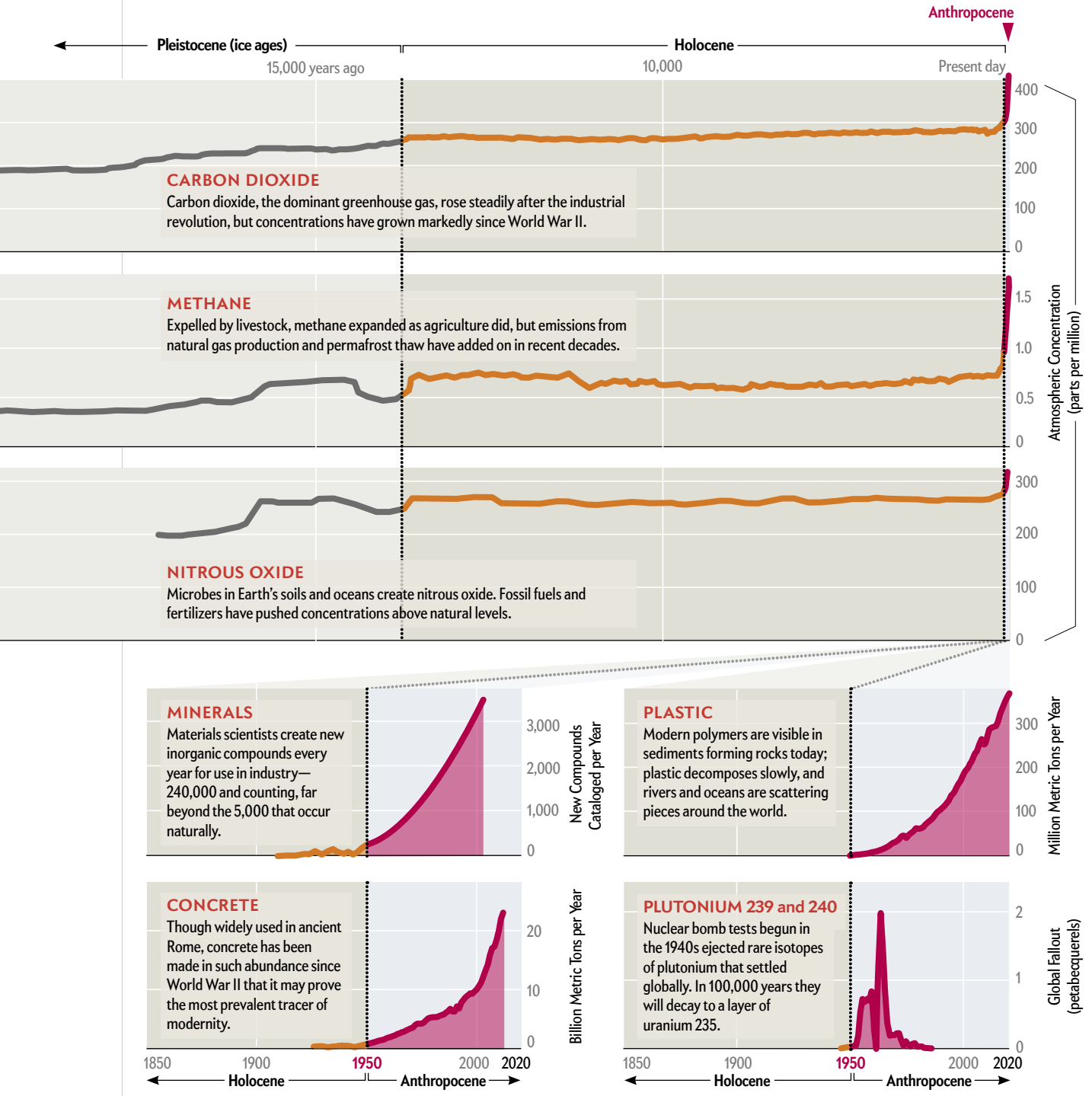
When Did the Anthropocene Begin?

The detritus of modern humanity is so pervasive that our "technofossils"—such as plastic and concrete—will permeate the rock that is forming today. Mounting evidence collected by scientists supports the idea that human activity has pushed the planet into a new geologic epoch: the Anthropocene. They say the epoch will prove distinct from the Holocene, which began when glaciers retreated 11,700 years ago—and that 1950 may be the logical threshold between the two. Markers of the Anthropocene (*shown here*) have spread across the globe, says geologist Colin Waters . "We've in effect become a new geologic force." —*Katie Peek*


Anthropocene
Pleistocene (ice ages)
Holocene
15,000 years ago
10,000
Present day
CARBON DIOXIDE
Carbon dioxide, the dominant greenhouse gas, rose steadily after the industrial revolution, but concentrations have grown markedly since World War II.
400
300
200
100
0
METHANE
Expelled by livestock, methane expanded as agriculture did, but emissions from natural gas production and permafrost thaw have added on in recent decades.
1.5
1.0
0.5
0
NITROUS OXIDE
Microbes in Earth's soils and oceans create nitrous oxide. Fossil fuels and fertilizers have pushed concentrations above natural levels.
300
200
100
0
Atmospheric Concentration (parts per million)
MINERALS
Materials scientists create new inorganic compounds every year for use in industry—240,000 and counting, far beyond the 5,000 that occur naturally.
3,000
2,000
1,000
0
New Compounds Cataloged per Year
PLASTIC
Modern polymers are visible in sediments forming rocks today; plastic decomposes slowly, and rivers and oceans are scattering pieces around the world.
300
200
100
0
Million Metric Tons per Year
CONCRETE
Though widely used in ancient Rome, concrete has been made in such abundance since World War II that it may prove the most prevalent tracer of modernity.
20
10
0
Billion Metric Tons per Year
PLUTONIUM 239 and 240
Nuclear bomb tests begun in the 1940s ejected rare isotopes of plutonium that settled globally. In 100,000 years they will decay to a layer of uranium 235.
2
1
0
Global Fallout (petabecquerels)
1850
1900
1950
2000
2020
Holocene
Anthropocene

Sources: "The Anthropocene Is Functionally and Stratigraphically Distinct from the Holocene," by Colin N. Waters et al., in *Science*. Vol. 351: January 8, 2016, and references contained therein; "A Bibliometric Study in Crystallography," by Heinrich Behrens and Peter Luksch, in Structural Science, Vol. 62: 2006 (*minerals data*)

Graphic by Katie Peek

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the animal species we have engineered to become our food make up most of the other two thirds. Wild animals, pushed to the margins, constitute 5 percent or less. In colonizing so much of the planet's land, we have comprehensively reshuffled what is left of wildlife, too, purposely or accidentally transporting animals and plants across the globe, homogenizing biology worldwide. We are also killing so many species that in another century or two Earth's biodiversity could take as catastrophic a hit as the one that happened when the dinosaurs disappeared. These transformations will show up in the distant future as a switch from one assemblage of fossils to another.

Humans have meanwhile taken the manufacture of "trace fossils"—such as footprints by dinosaurs and burrows by sea worms—to completely new levels. Our mines and boreholes penetrate several kilometers into the ground, so deep that these traces permanently scar the planet. The towns and cityscapes that have made over Earth's surface are also mirrored in subsurface foundations, pipelines and subway systems.

PERMANENT OR FLEETING?

ALL IN ALL, we humans have left a formidable catalog of new geologic signatures. Will these effects *permanently* reconfigure Earth's strata and future history, defining a formal new epoch? Or, with humans gone, will systems spring back to normal, eroding our constructions into dust, like the fate of the mighty Ozymandias empire in Percy Bysshe Shelley's poem of the same name? It is still early days.

Luckily, four billion years of strata have left us a few lessons. Where Earth's crust is rising, such as on growing mountain ranges, surface structures are indeed eroded and washed away as sedimentary particles into some far-off sea. Where the crust is subsiding—as below many of the world's major deltas—the strata piling up can preserve even seemingly ephemeral traces such as leaves, twigs and footprints. Therefore, San Francisco, pushed up by tectonic forces, seems destined to be weathered away. Sinking New Orleans, Shanghai and Amsterdam, however, will leave ample traces of their massive, complex structures, together with aluminum, plastic, ceramics—and skeletons with metal-filled teeth and artificial hips. When these strata are ultimately pushed up high by tectonic forces, millions of years from now, the newly minted cliffs will reveal a distinctive Anthropocene layer.

The permanence of fossils, and of long-term consequences of our actions, figures in the answer, too. The meteorite strike that ended the Cretaceous period was instantaneous; the immediate shock wave was over in hours. But its effects reshaped biology for millions of years, and the reverberations are still with us today. Without that meteorite, we might not be here now; dinosaurs might still be ruling the globe.

Humanity's impact, swift though not that sudden, could likewise change the planet in ways that will be felt long after we disappear. Many trends are accelerating, and some—species extinction, climate change and sea-level rise—are only in their early stages. Regardless of when the fossil-fuel era finally ends, its effects will diminish only slowly, over many millennia. (And human civilization, which developed in the environmentally stable Holocene, will have to adapt to an unstable, changing planet for many generations.)

We may exert long-term influence in another way as well. Humanity is a much more complex, protean planetary force than a meteorite strike or glacial retreat. Our extraordinary geologic power is driven by our intelligence, our manipulative ability and our hypersocial interactions that pass on new knowledge. These traits have allowed us to develop the technology that now keeps us alive, and that itself is evolving at an accelerating rate, literally from year to year.

This emergent technosphere, as Duke University professor emeritus Peter Haff calls it, can be considered an outgrowth of the biosphere. It has its own dynamics, over which we have only partial control. It includes the possibility that a silicon-based intelligence could soon vie with our own. Among all the ongoing global changes that will determine Earth's geologic future, the technosphere is the wild card. It could produce a revised Anthropocene planetary state—but humans may no longer be calling the shots. For now scientists can decide only how to characterize the present. Should an Earth that is rapidly, profoundly and permanently being transformed by humans be formally recognized in a new epoch in the geologic timescale?

For the geologists who would make the determination, the jury is still out. Important decisions need be made. When would the Anthropocene have begun, for instance? Suggestions have ranged from thousands of years ago, when human impacts first became discernible, to far into the future, once our impacts are fully expressed. For practical purposes, the most suitable boundary seems to be the extraordinary "great acceleration" of population, energy use and industrialization that began in the mid-1900s. Strata after that time are marked by strong increases in amounts of concrete, plastics, plutonium and the remains of a transformed biology.

Geologists are searching for a suitable "golden spike"—a carefully selected reference that serves as a global marker for a new epoch. Would that be provided by the radioactive nuclei or carbon particles trapped in the snow and ice layers of Greenland and Antarctica, in sediment layers in far-flung lakes and fjords, and on undisturbed seafloors? Or might it be some other indicator, a telltale change in living chemistry preserved within tree rings and annual coral growth bands? The hunt is on. SA

Jan Zalasiewicz is an emeritus professor at the University of Leicester in England and is a member of the Anthropocene Working Group of the International Commission on Stratigraphy. He has a particular fondness for graptolites—an extinct form of plankton.

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Illustration by Andrea Ucini

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The Environmental Cost of Inequality

Power imbalances facilitate environmental degradation—and the poor suffer the consequences

By James K. Boyce

IN THE FALL OF 2016 AN ENVIRONMENTAL STRUGGLE IN RURAL NORTH DAKOTA MADE headlines worldwide. The local Standing Rock Sioux Tribe and climate activists were pitted against the corporate and government backers of the Dakota Access Pipeline, which was being built to carry oil from the state's Bakken shale fields to a terminal in Illinois. Private security guards unleashed attack dogs on protesters, and the police blasted them with water cannons in freezing weather.

The tribe feared that a leak in the pipeline as it crossed under a reservoir along the Missouri River would contaminate its water supply. Climate activists joined the protest to fight ramped-up extraction of fossil fuels. Supporters of the $3.8-billion project argued that it would save the oil industry money, being less costly than the alternative of oil shipment by rail, and that its construction would bring jobs with multiplier effects to the local economy. Because the price of oil is set on world markets, the cost savings would not mean lower prices for consumers—but it would bring higher profits to producers.

By December 2016 the U.S. Army Corps of Engineers announced that it would deny approval for the pipeline crossing, a decision greeted with whoops of joy at the protesters' encampment. But four days after taking office in January, President Donald Trump overturned the ruling, and a few months later the oil began to flow.

The battle reflected what seems to be a basic reality: When people who could benefit from using or abusing the environment are economically and politically more powerful than those who could be harmed, the imbalance facilitates environmental degradation. And the wider the inequality, the more the damage.

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Furthermore, those with less power end up bearing a disproportionate share of the environmental injury.

We see these situations all around us. Polluting power plants and hazardous waste dumps are located in poor neighborhoods. Drinking-water impurities afflict minority communities. But is this relation between power and environmental degradation consistently true? If so, why? And what can we do about it? At Standing Rock, the balance between the opposing sides was close; Trump's election was enough to tip the scales. But the experience, along with some recent shifts in power balances, offers lessons—and even hope—that efforts to reduce economic and social inequality will be good not only for people but also for the environment.

GREATER INEQUALITY, GREATER HARM

RESEARCH on the connection between social power and environmental degradation began in earnest in the 1990s. Economists reported that they had found an inverted U-shaped relation between pollution and per capita income. They plotted air and water pollution on the *y*-axis of a graph and average income on the *x*-axis, comparing dozens of countries. Pollution initially increased as income went from $0 to a turning point of up to about $8,000 a year. But after that, pollution decreased as income rose further. This became known as the environmental Kuznets curve because of its similarity to the relation between inequality and average income found in a famous 1955 study by economist Simon Kuznets.

The environmental Kuznets curve appeared to offer respite from the bleak assumption that rising production and consumption necessarily lead to more environmental damage. Maybe humans were not, as environmental historian Roderick Nash once put it, a "cancerous" species whose growth "endangers the larger whole." A spirited debate ensued among analysts who saw economic growth as the solution to environmental woes and those who still saw it as the crux of the problem.

I was not convinced by either side. Maybe that was because in my 20s, I had lived among some of the world's poorest people in a Bangladesh village. That experience left me with the indelible understanding that human societies cannot be neatly summed up by population or per capita data. Many Bangladeshis went hungry but not because the country had too many people or too little food per person. There was enough food for everyone, yet communities starved because the poor lacked the purchasing power to buy it in the market and the political power to obtain it by other means. In his 1981 book *Poverty and Famines,* economist Amartya Sen explains that famines typically arise from similar realities. Inequality in the distribution of wealth and power seems to be central to how societies function and malfunction.

In thinking about the original and environmental Kuznets curves, it occurred to me that inequality, not per capita income, might underlie environmental degradation: the two seemed to rise and fall together. When then Ph.D. student Mariano Torras and I reanalyzed the environmental Kuznets curve data in 1998, we found that countries with lower rates of adult literacy, fewer political rights and civil liberties, and higher income inequality—which we considered to be indicators of more unequal distributions of power—tended to have more polluted air and water. After controlling for these indicators, the apparent effect of per capita income weakened, and for some pollutants, it disappeared entirely. We also found that greater inequality was associated with less access to clean drinking water and sanitation facilities, both crucial to the environment and human well-being.

In a 1999 follow-up study, my co-authors and I examined the 50 U.S. states. We analyzed the relation between the strength of state environmental policies and the distribution of power, using as proxies the rate of voter participation, the percentage of adults completing high school, tax fairness and Medicaid access. We found that wider inequality was associated with weaker environmental policies and that weaker policies were associated with more environmental stress and poorer public health. These results suggested that the pathways by which inequality adversely affects health include not only physiological stress, violence and reduced access to health care—all of which had been documented by public health researchers—but also impacts on the environment.

The initial reactions to our findings were decidedly cool. In the 1990s, when free markets and deregulation were all the rage, concerns about inequality were brushed aside as passé, maybe even soft-headed. One reviewer claimed that I was "beating a dead horse."

In the 2000s, however, inequality reemerged as a central political issue. The growing gap between the "1 percent" and everyone else, the terrible toll of Hurricane Katrina on low-income residents in New Orleans and the economic dislocations that followed the 2008 financial crisis all helped to put it back on the agenda. At the same time, evidence mounted that more concentrated wealth and political power leads to worse environmental performance—and not just in terms of air and water pollution. Researchers found that the proportion of plants and animals threatened with extirpation or extinction is higher in countries with more unequal income distributions. Rates of deforestation are higher in countries with greater corruption. Public expenditure on environmental research and development and patents on environmental innovations are lower in industrial nations with greater income inequality. More inequality has also been linked to higher carbon emissions per person and per unit of gross domestic product.

These findings make sense when we consider that with less inequality, people are better able to defend the air, water and natural resources on which their health and well-being depend. Protecting the environment and reducing inequality go hand in hand.

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POWER RULES

ANY ACTIVITY THAT CAUSES environmental degradation generates winners as well as losers. The activity benefits some people—otherwise no one would pursue it. And some people bear the costs—otherwise the degradation would not be seen as a problem. This poses a basic question: Why can those who benefit from such activities impose environmental costs on others?

There are three possible answers, all of them related to power disparities. One is that the costs are deferred, borne by future generations, who are not here today to defend themselves. In such cases, as when we think of the long-term impacts of climate change, the only way to safeguard the environment is for those of us who are alive to take responsibility toward those "whose faces are yet beneath the surface of the ground, the unborn of the future Nation," in the words of the Iroquois Constitution.

A second possibility is that people who are harmed are unaware of being hurt or do not know where the harm comes from. They may realize, for example, that their children are getting sick but not that the illness can be traced to emissions from a nearby refinery or power plant. In such cases, the solution lies in greater access to knowledge and, in particular, in policies that guarantee the public's right to know about environmental hazards and their sources.

The final possibility is that even when people are well aware that they are bearing the brunt of environmental costs and know the sources, they lack sufficient economic and political power to prevail in social decisions about the use and abuse of the environment. Standing Rock is an example. The solution in such cases is to change the balances of power.

Government decisions affecting the environment often invoke a cost-benefit analysis: How much benefit can be gained and at what cost? In this calculation, economic power (also known as purchasing power) plays a key role. People with more dollars effectively wield more "votes."

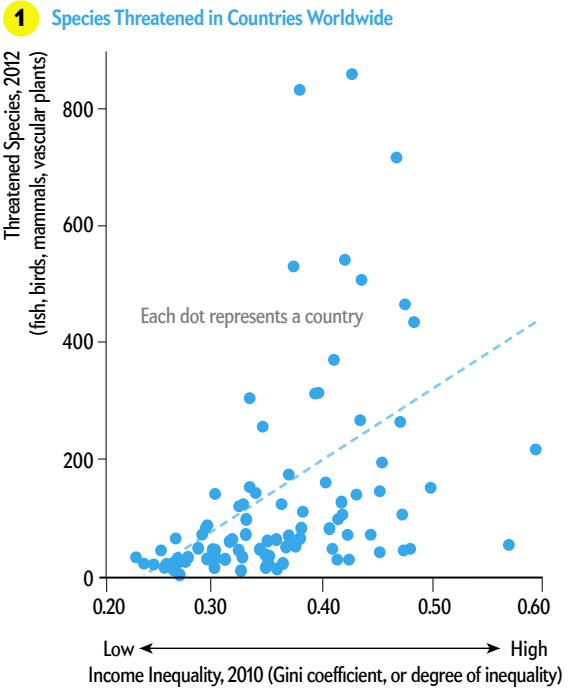
When the people who could be harmed have little or no political power, decision makers can minimize or ignore the costs. An extreme example is the cost-benefit case the U.S. Environmental Protection Agency made under the Trump administration for repealing the Clean Power Plan. It assigned a value of zero to all climate impacts outside the U.S., reasoning that harms to people not in the country should not be considered in the making of U.S. climate policy.

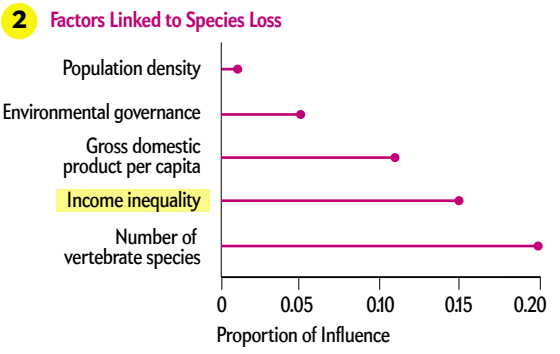
Purchasing power and political power tend to be correlated: those with more dollars often have more political influence, and vice versa. Their joint effect can be described by a concept I call the power-weighted social decision rule. It means that the weight assigned to the costs and benefits from environmentally degrading activities depends on the power of the people to whom those accrue. When those who benefit from environmentally degrading activities are wealthy and powerful, compared with those who are harmed, social decisions favor the winners over the losers. The greater the inequality between rich and poor and between the more powerful and the less powerful, the greater the extent of environmental degradation.

Power inequality also exacerbates the neglect of future generations and lack of knowledge about environmental costs. When inequalities are wide, the imperatives of day-to-day survival for the very poor may overshadow worries about tomorrow; among the

MORE INEQUALITY, FEWER SPECIES

Many studies show that as the gap between rich and poor people widens, the extent of environmental damage increases. For example, one analysis found that countries with higher income inequality also have higher rates of species classified as threatened by the International Union for Conservation of Nature (1). A separate report determined that income inequality is more strongly correlated with species loss than other major factors such as population density and even environmental policies (2). Only the total number of species had greater influence.





Sources: "Inequality and Environmental Sustainability," by S. Nazrul Islam. United Nations Department of Economic and Social Affairs Working Paper No. 145. United Nations, August 2015 (*number of species threatened*); "A Cross-National Analysis of How Economic Inequality Predicts Biodiversity Loss," by Tim G. Holland, Garry D. Peterson and Andrew Gonzalez, in *Conservation Biology*, Vol. 23, No. 5, October 2009 (*factors linked to species loss*)

Graphics by Jen Christiansen

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OBJECTION to the Dakota Access Pipeline in North Dakota by local Native Americans concerned about contaminated water supplies grew to a larger protest nationwide against corporations and politicians having more power than underserved communities.

Jim Watson *Getty Images*

very rich, fear that their sway will eventually end can foster a cut-and-run attitude toward natural resources (exemplified by the rapacious deforestation of Southeast Asia in the 1960s and 1970s under such dictators as the Philippines' Ferdinand Marcos and Indonesia's Suharto). And when inequalities are wide, the poor are more likely to lack access to information, including about the nature and causes of the environmental harms to which they are subjected.

HEADS I WIN, TAILS YOU LOSE

THE POWER-WEIGHTED social decision rule predicts not only that greater inequality will lead to greater environmental harm but also that the harm will be concentrated in communities at the lower end of the wealth-and-power spectrum. In those places, environmental costs carry less weight in the eyes of decision makers. Racial and ethnic minorities and low-income communities are at greatest risk. The Standing Rock reservation, where more than 40 percent of residents fall below the federal poverty line (triple the national rate), was vulnerable on both counts.

At the same time, the benefits from environmentally degrading activities—higher profits for producers and lower prices for consumers—are concentrated at the upper end of the economic spectrum. Profits flow to shareholders and corporate executives, who generally are relatively well off. And the more that consumers spend, the more they benefit from lower prices, again bestowing greater benefits on the well-to-do.

This is not to say that affluent people do not want a clean and safe environment. But to a substantial extent, environmental quality is what economists call an impure public good. It is not equally available to everyone. Well-off people can afford to live in cleaner places, buy bottled water and air conditioners, and get better medical care. They can also more effectively oppose having environmental hazards placed in their neighborhoods. By being further removed from environmental harms, they can more easily afford to ignore them. Even when they cannot altogether escape the consequences of environmental degradation, they weigh a relatively small share of the costs against a relatively large share of the benefits.

ENVIRONMENTAL INJUSTICE

SINCE THE 1980S researchers have systematically documented the disproportionate exposure of racial and ethnic minorities and low-income communities to environmental hazards in the U.S. One of the earliest studies, by sociologist Robert Bullard, examined the spatial distribution of hazardous-waste sites in Houston and found them to be located primarily in Black neighborhoods.

Subsequent studies have revealed similar patterns in many parts of the country: race and ethnicity correlate strongly with proximity and exposure to environmental harms. In multivariate analyses, race and ethnicity turn out to be even stronger predictors of pollution exposure than low income, testifying to the enduring salience of racism in the distribution of power in the U.S. The most hard-hit communities are often those where disadvantages of race and class intersect.

Researchers have also investigated how the correlations can be explained. One controversy that arose was about timing: Are hazardous facilities sited from the outset in communities with less wealth and power? Or, after a facility is sited, do wealthier residents move out, property values decline and poorer people move in? Few studies have explored this question directly, but those that do have found strong evidence that such toxic facilities are sited from the start in communities with less power. The evidence also indicates that in cases where more well-to-do people leave after a facility is built, the trend had already begun before the sit-

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ing, suggesting that communities in transition are more vulnerable to having environmental hazards imposed on them.

Disproportionate pollution exposure hurts children in particular, resulting in higher rates of infant mortality, lower birth weights, a higher incidence of neurodevelopmental disabilities, more frequent and intense asthma attacks, and lower school test scores. Among adults, exposure is linked to work days lost to illnesses and the need to care for sick children. Over time these health effects reinforce the disparities that make communities more vulnerable to environmental harm in the first place.

Although the effects are most severe for at-risk communities, they often spill over to wider populations. For example, U.S. metropolitan areas with more residential segregation along racial and ethnic lines tend to have higher cancer risks from air pollution for everyone, not only for people of color. In cities that rank in the top 5 percent nationally for racial and ethnic disparities in industrial air pollution exposure, the average exposure for non-Hispanic whites is significantly higher than in those where pollution disparities are smaller. Environmental justice is good for everyone.

Environmental inequalities can be found everywhere. In England and the Netherlands, poorer and more nonwhite neighborhoods have higher air concentrations of particulate matter and nitrogen oxides, which aggravate respiratory problems. In Delhi, whose residents breathe some of the world's dirtiest air, the poor live in some of the most polluted neighborhoods. They also spend more time working outdoors, including along roadways, where air pollution loads are most extreme. They cannot afford air conditioning or air purifiers. At the same time, they obtain fewer benefits from the power generation, transportation and other industries that cause the pollution.

The power-weighted social decision rule operates at the international scale, too. Environmental harm is unduly inflicted on the poorest countries. In a 1991 memorandum, Lawrence Summers, then chief economist at the World Bank, wrote that "the economic logic behind dumping a load of toxic waste in the lowest-wage country is impeccable" because the foregone earnings from illnesses and deaths there will be lowest. His statement may have been tongue-in-cheek, but environmental practice often follows this script. Every year millions of tons of toxic waste are shipped from advanced industrial countries to low-income nations in Africa, Asia and Latin America.

The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal, an international environmental agreement that took effect in 1992, has proved inadequate to halt this flow. The distance between people who benefit from the economic activities that generate the waste and those who bear the costs of its disposal gives a painful new twist to the adage "out of sight, out of mind."

THE NEW ENVIRONMENTALISM

SO WHAT CAN WE DO to lessen social and environmental inequality, thereby reducing harm to people and the planet? The relation between inequality and the environment is a two-way street. Reducing inequality in the distribution of wealth and power helps to bring about a greener environment. And efforts to advance the right to a clean and safe environment help to bring about greater equality. The key to both is active mobilization for change.

U.S. environmentalism in the 20th century aimed to protect nature from people. Enlightened elites often saw themselves as defenders of nature from the irresponsible masses. From there it was a short step to assume an inexorable trade-off between environmental protection and broad-based economic well-being.

When people who could benefit from using or abusing the environment are economically and politically more powerful than those who could be harmed, the imbalance facilitates environmental degradation.

In the 21st century we are witnessing the ascendance of a new environmentalism. The aim is to protect individuals who face harm from people who profit from degradation. The balance of power between these two sides can and does change over time. When climate activists from across the country joined Native Americans at Standing Rock, defending their right to a clean and safe environment, the power-balance scales began to move. The protesters, building on past achievements of movements across the country for equal rights and environmental protection, again came close to halting a multibillion-dollar enterprise in 2020, when a federal judge ordered the Army Corp of Engineers to undertake a new environmental review of the pipeline. A 2021 ruling allows the pipeline to remain in operation during the review.

Similarly, in Washington State, activists succeeded in blocking a proposed coal export terminal that would have been the largest in the country, protecting lands and waters of tribal communities. In Montana, the Blackfeet Nation won the cancellation of energy leases on 23,000 acres, the culmination of a 30-year struggle.

The intimate links between inequality and the environment have led to growing recognition that if we want to rebalance human relationships with nature, we also need to rebalance our relationships with one another. SA

James K. Boyce is a professor emeritus of economics and senior fellow at the Political Economy Research Institute at the University of Massachusetts Amherst. He is author of *Economics for People and the Planet: Inequality in the Era of Climate Change* (Anthem Press, 2019).

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THE ARCTIC CLIMATE IS SHATTERING

MELTD

ICEBERGS launched from Greenland's fast-moving Jakobshavn glacier float past the town of Ilulissat under the midnight sun.

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RECORD AFTER RECORD, ALTERING WEATHER WORLDWIDE

By Jennifer A. Francis

OWN

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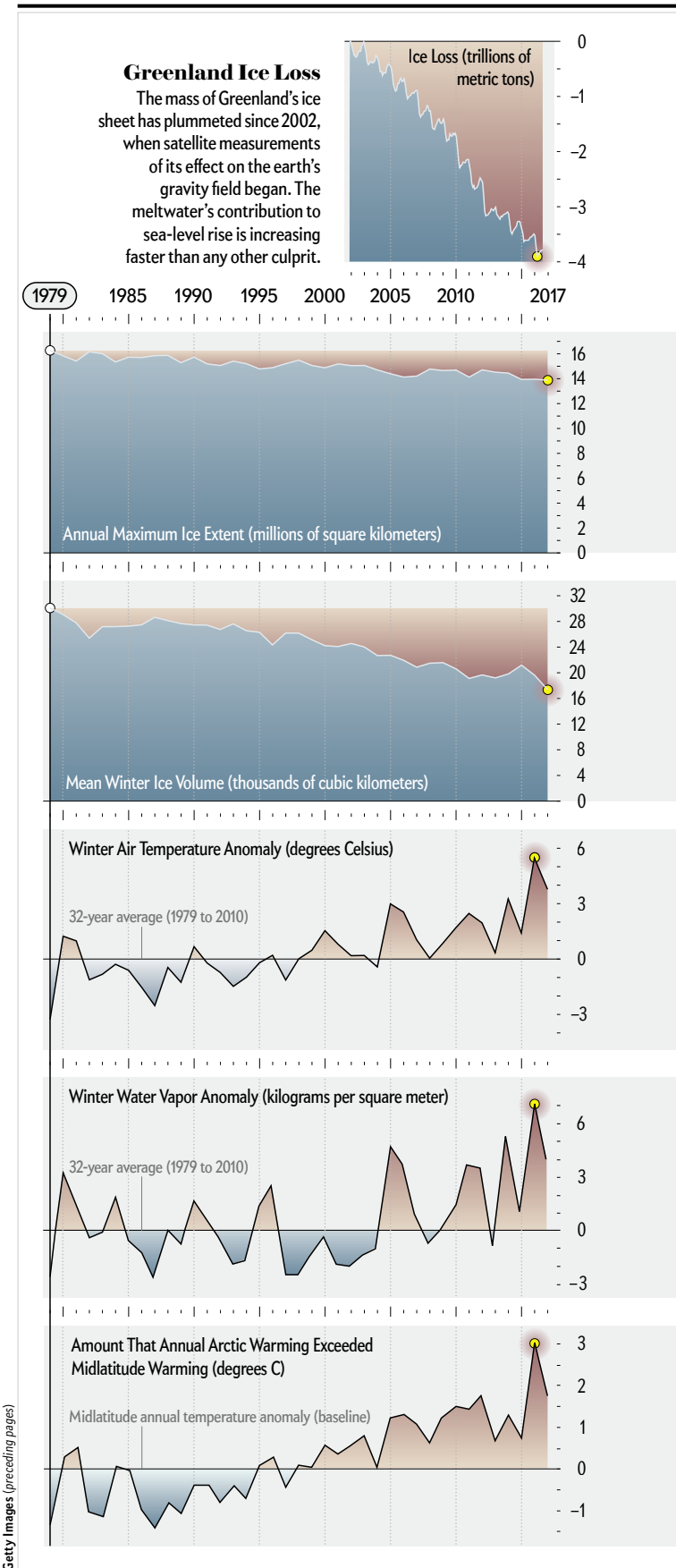
TWENTY-FIVE SCIENTISTS, including me, had an epiphany about the Arctic in 2003. The National Science Foundation had invited us to a retreat in Big Sky, Mont. Before this gathering, each of us had been focusing our Arctic research on our own narrow topics. As we shared our perspectives, we came to a frightening realization: the changes we had been finding individually were connected. They fit together perfectly. The Arctic system as a whole was careening toward a precarious new state. And hope of stopping it already seemed unlikely.

We published a paper with a stunning, controversial conclusion: At the current rate of change, there was a real possibility that within a century, the world could witness a summer Arctic Ocean that would be ice-free, a state not seen for thousands of years. Today I am startled again because it now appears that the ocean will likely be free of summer ice by 2040—a full 60 years earlier than we had predicted more than a decade ago.

The Arctic is changing exactly the way scientists thought it would but faster than even the most aggressive predictions. The recent behavior is off the charts. Since just 2015, more than a dozen climate records that had each stood for many decades have crumbled, including those for disappearing summer sea ice, decreasing winter sea ice, warming air and thawing ground.

These trends signal trouble for people around the world. The last time the Arctic was only slightly warmer than today—about 125,000 years ago—oceans were 13 to 20 feet higher. Goodbye, Miami, New Orleans, the naval base in Norfolk, Va., most of New York City and Silicon Valley, as well as Venice, London and Shanghai. New research suggests that rapid Arctic warming also tends to reroute the jet stream in ways that could allow punishing weather patterns to linger across North America, central Europe and Asia longer than usual, subjecting millions of people to unyielding heat waves, droughts or relentless storms. Plankton are increasing throughout the southern Arctic Ocean, which may disrupt food chains that support commercial fisheries. And the massive ice melt is adding to an enormous blob of freshwater south of Greenland that may be slowing the Gulf Stream, which could significantly change weather patterns for continents on both sides of the Atlantic Ocean.

What's driving this breakneck change?



Getty Images *(preceding pages)*

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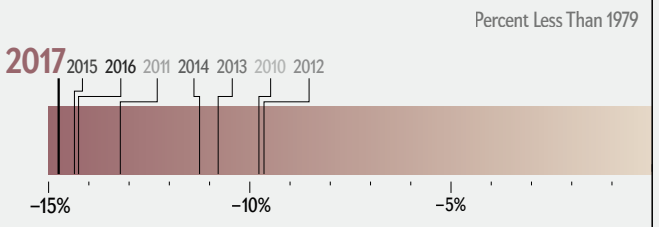
Record-Breaking Arctic

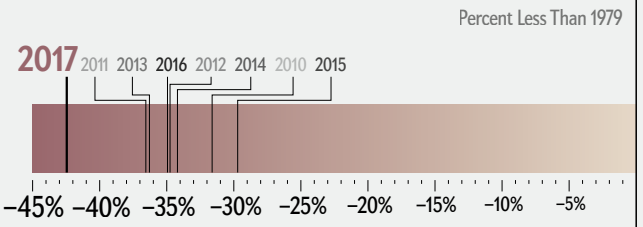
The Arctic region is changing dramatically, and the rapid transformation will affect billions of people around the world. Between 2015 and 2018 (the latest data available at the time of reporting), numerous climate records up north were broken, in some cases by stunning margins. Six notable examples are shown here. Red numbers in the bar charts indicate all-time records; values for recent years reflect a trend toward those excesses. Individually, the effects alter the environment and daily life for people throughout the region. Together the effects are reshaping weather across the Northern Hemisphere, culminating in Arctic amplification (*final graph*), which raises the chance for extreme conditions year-round.

Value in 1979



Winter Sea-Ice Extent

As winter deepens, ice spreads over the Arctic Ocean. But the maximum reach has declined steadily, especially across the Barents and Bering Seas. Less ice cover allows the open ocean to send more heat and moisture into the air, significantly disrupting Arctic weather.

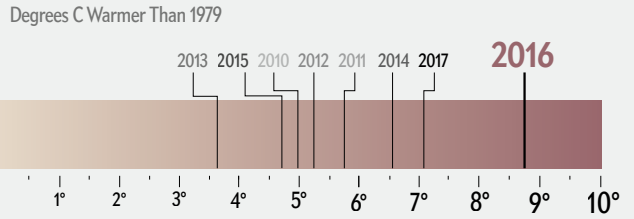


Winter Sea-Ice Volume

By 2017 the amount of winter ice floating on the Arctic Ocean had dropped an astounding 42.5 percent since 1979. Winds can more easily push thin ice, trapping ships and coastal communities. Thinner ice also melts faster in warm months; summer ice volume dropped 80 percent in the same time span.

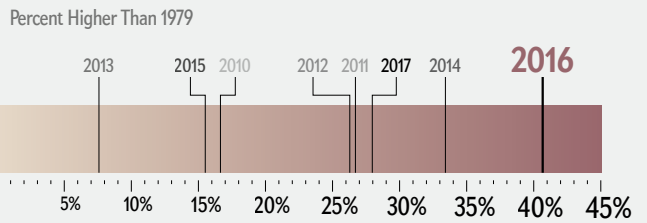
Winter Air Temperature

On certain days Arctic temperatures can soar 20 degrees Celsius above normal, and they are now elevated throughout most winters. In 2016 the mean winter temperature was almost nine degrees higher than in 1979. This trend can weaken the jet stream, bringing deep cold snaps and snows to the U.S., Europe and Asia.



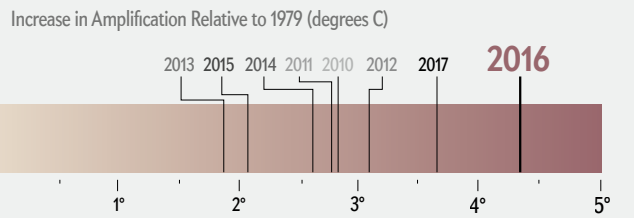
Winter Water Vapor

With less ice cover, more open ocean sends added moisture into the air. Even a small rise has big, underappreciated consequences: water vapor is a greenhouse gas that traps heat. It also condenses into clouds, releasing its latent heat. The clouds can enhance warming, too.



Arctic Amplification

The Arctic is warming faster than the rest of the world. This "amplification" means the average temperature in the Arctic is getting closer to the average temperature in the midlatitudes. The narrowing gap slows the jet stream year-round, raising the chances across the Northern Hemisphere for more persistent, extreme weather patterns—among them heat waves, floods, cold spells and maybe even longer-lasting hurricanes.



Sources: JPL Grace Mascon Ocean, Ice, and Hydrology Equivalent Water Height RL05m.1 Cri Filtered Version 2. D. N. Wiese, D.-N. Yuan, C. Boening, F. W. Landerer and M. M. Watkins. Po.daac, JPL. April 29, 2016. Data accessed February 14, 2018 (*Greenland ice*); Japan's National Institute of Polar Research and Jaxa, via Arctic Data Archive System (*ice extent*); Piomas, Polar Science Center (*ice volume*); Ncep/Ncar Reanalysis 1, Physical Sciences Division, Esrl, NOAA (*air temperature, water vapor anomaly* and *amplification data*)

Graphic by Pitch Interactive

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LOSS OF "PERMANENT" ICE

SCIENTISTS EXPEND A LOT OF ENERGY watching the Arctic because it is so sensitive to climatic change. It is a "canary in the coal mine" for the earth's entire climate system. The long list of records that have been smashed during the past several years leaves no doubt that decades of unnerving climate simulations are on target. But the data say something even greater: our projections of changes on the way may be far too conservative.

In only 40 years the extent of ice across the Arctic Ocean in summer has shrunk by half. Yes, half. The volume of sea ice, year-round, is way down, too—about a quarter of what it was in the early 1980s. Until recently, scientists had thought it would take until at least the middle of this century to reach these extremes.

Summer sea ice is vanishing quickly because of feedbacks—vicious cycles that can amplify a small change. For example, when a bit of extra heat melts bright-white ice, more of the dark ocean surface is exposed, which reflects less of the sun's energy back to space. That absorbed heat then warms the area further, which melts even more ice, leading to yet more warming. In winter when the sun is not shining, other feedbacks take over. For example, sea ice floating on the Arctic Ocean acts like an insulating sheet, preventing heat and moisture under it from escaping into the atmosphere. When that ice recedes, more heat and moisture can warm the air, further retarding ice formation. Computer simulations generally show ice disappearing too slowly, contributing to the conservative estimates of future warming.

Disappearing sea ice is not the only transformation keeping researchers like me awake at night. The other two types of what used to be called permanent ice in the Arctic are also declining steeply.

Permafrost—soil that usually remains frozen year-round—has been thawing. Buildings constructed atop permafrost are collapsing, trees are toppling and roads are buckling. In addition to disrupting daily life for local residents, thawing soils also can release large quantities of heat-trapping gases into the atmosphere. When the organic matter that has been locked in permafrost for thousands of years thaws, bacteria break it down into carbon dioxide (if oxygen is present) or methane (if it is not). Arctic permafrost contains about twice as much carbon as the atmosphere holds now, so widespread thaw could greatly exacerbate global warming—which would lead to even faster thaw. Today's computer models do not adequately capture the impacts of thawing permafrost, again contributing to substantial underestimates of future global warming.

The third type of previously permanent Arctic ice is the frozen water on land, including glaciers and Greenland's enormous ice cap, which is more than a mile thick on average. Losing this ice has dire consequences worldwide because, unlike melting sea ice, the runoff into the ocean raises sea level directly. During the summer of 2016 the total mass of Greenland's ice sheet (estimated using satellite measurements of how it affects the earth's gravity) reached the smallest value since satellite observations began in 2002. The levels are also lower than any amount going back to the late 1950s, when the mass was estimated in other ways. A recent investigation suggests that the accelerating ice melt on Greenland's surface is hastened by warming effects linked to dwindling sea ice.

HOTTER, WETTER AIR

REDUCED SEA ICE and rapid Arctic warming have other far-reaching effects. The combination may alter upper-level winds so that they carry additional heat and moisture from southerly latitudes toward the North Pole. In 2012 the then record Greenland surface melt resulted from an unusually strong and persistent ridge of high pressure in the atmosphere—a so-called blocking high. It brought not only heat and moisture from the south but also soot from wildfires around the Northern Hemisphere. That soot darkens ice and snow surfaces (lowering its albedo, or reflectivity), which then absorb more of the sun's energy, accelerating melt—another one of those vicious cycles.

Strong Arctic warming can lead to prolonged heat waves, stalled hurricanes, relentless rains and more intense fire seasons.

Blocking patterns—large eddies in the jet stream—near Greenland appear to be occurring more often in recent decades, especially in summer months, which probably accounts for at least part of the upward trend in melting. Ice-mass loss during 2018–2019 set a new record, topping 2010 and 2012. Recent work by my colleagues and me suggests that the greater number of blocking highs most likely is tied to global warming. Computer simulations struggle to form and break down blocks realistically, however, so it is hard to say how these patterns may act in the future.

Other Arctic behavior is equally outlandish. During the winters since 2016, record-breaking heat waves near the North Pole were surpassed by more record-breaking heat waves. Waning and thinning sea ice is part of the cause, providing less of a barrier for the ocean's heat to enter the air. The jet stream's wild north-south swings also brought record pulses of warmth and moisture to far northern latitudes. Scientists and Arctic residents often fail to appreciate the strong effects that the extra moisture can create. For starters, water vapor is a greenhouse gas, so in a dry Arctic winter atmosphere, a little more moisture can trap substantially more heat. Moreover, when that moisture condenses into clouds, it releases latent heat, further warming the air. Finally, more clouds trap more warmth below them, one more factor contributing to the Arctic meltdown.

STUCK IN EXTREMES

ALTHOUGH WE HAVE MORE TO LEARN, it has become clear that rapid Arctic change is underway, the most dramatic in human history. Given this stark reality, atmospheric scientists are trying to pin down the effects that the changing Arctic may

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MELTWATER atop a disintegrating ice cap in Svalbard, Norway, pours into the sea.

Getty Images

have on people and ecosystems around the world so society can decide how to react and prepare for the future.

An obvious example of global effects is coastal flooding. According to a 2017 report by the Union of Concerned Scientists, about 170 U.S. coastal communities will experience chronic inundation within 20 years. By the end of this century, if nations keep emitting carbon dioxide as they have been, most large coastal cities around the world will face regular, disruptive flooding. This eerily prescient report was published just weeks before Hurricanes Harvey, Irma and Maria capped the U.S.'s most destructive and costly hurricane season ever.

There is also mounting evidence that strong warm-ups in the Arctic's lower atmosphere can affect winds in the jet stream and even higher, in the stratosphere, home to the polar vortex wind pattern that circles the Arctic. Northward peaks and southward valleys in the bending jet stream generate the high- and low-pressure centers we see on weather maps as a capital H or L. The bends control our weather in the Northern Hemisphere. But if extremely large bends occur more often, we can expect to see an uptick in extreme conditions where billions of people live. That is because large bends in the jet stream tend to progress more slowly from west to east, causing the weather systems they create to hang around longer. Think prolonged heat waves, relentless rains and stalled tropical storms like Hurricane Harvey, which swamped Houston in August 2017—as well as more intense fire seasons like the ones California has experienced in recent years.

Large waves in the jet stream, along with strong Arctic warming, can disrupt the polar vortex, prolonging deadly deep freezes or parades of snowstorms, including the devastating stretch of severe cold that gripped the lower Midwest U.S. in February 2021. A polar vortex collapse can also perpetuate wild jet-stream swings that deliver intense heat waves to Alaska and the far north, creating yet another vicious cycle that accelerates Arctic warming. Some studies suggest that Arctic warming is closely connected with these wavy patterns; others say proof of the connection is still tenuous. Research on this hot topic is advancing quickly.

A rapidly warming Arctic most likely will significantly alter habitats on land and at sea. Already, as sea ice recedes, plankton blooms have appeared in new areas during new seasons, enticing species of fish from lower latitudes to move into Arctic waters while native fish disappear. Earlier spring snowmelt across high latitudes has led to earlier greening of the tundra and earlier hatching of insects; migrating birds, which take their cues from the length of daylight hours, may arrive at Arctic food sites too late for the feast. Peoples of the Arctic are feeling the impacts, too; melting ice is keeping them from traditional hunting grounds and even forcing them to uproot towns threatened by coastal erosion from high storm waves in areas that used to be protected by ice along the shore. At the same time, big countries and big companies are swooping in to search for newly accessible natural resources, as tensions rise over who can claim which parts of the vast, rich seabed as theirs.

The revelation my colleagues and I had at the Big Sky retreat replays in my head every time another long-lived weather pattern wreaks havoc or another Arctic record is broken. Now my neighbors are catching on. Polls suggest that most Americans think that the loss of Arctic ice and the jet stream—which has fast become a household term—are conspiring to create weird weather. The old Arctic may have been ruthless, but it was stable. The new Arctic is less predictable and may be changing in ways that are irreversible, with ripple effects on life around the globe.

Are these impacts still avoidable? Yes and no. Because the climate's response lags behind the increases in greenhouse gas concentrations and because carbon dioxide has a very long lifetime in the atmosphere, future change is already baked into the system. But the magnitude and pace can be reduced if society moves quickly to drastically cut emissions and if methods can be developed to extract carbon from the atmosphere in large quantities. Progress on both these fronts is rapid, though likely too little, too late, to preserve the earth and the Arctic as we have known them. Prepare for the unexpected. SA

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A TAPESTRY OF ALTERNATIVES

Making peace with the biosphere will require building communities and relationships that are focused on sustaining life—human and nonhuman

Text and photographs by Ashish Kothari

INDIGENOUS SEEDS, nourished by rainwater and organic supplements, help Nadimidoddi Vinodamma of the Deccan Development Society (DDS), a farmers' cooperative in southern India, grow enough food for her family as well as to sell in local markets.

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NO ONE IN HER VILLAGE FACED FOOD SHORTAGES DURING THE lockdowns, nor did they suffer from COVID-19, Moligeri Chandramma assured me through an interpreter in March 2021. A farmer in the drylands of southern India, she grows more than 40 species and varieties of crops—mostly native millets, rice, lentils and spices—on a bit more than a hectare of land. Chandramma is a member of the Deccan Development Society (DDS), a cooperative of nearly 5,000 Dalit (oppressed caste) and Adivasi (Indigenous) women whose remarkable integration of biodiversity conservation with agricultural livelihoods earned them the United Nations' prestigious Equator Award in 2019. Emerging from a situation of extreme malnutrition and social and gender discrimination in the 1980s, these farmers now enjoy food sovereignty and economic security. Beyond simply weathering the pandemic, in 2020 each family in DDS contributed around 10 kilograms of food grains to the region's relief effort for those without land and livelihoods.

On the other side of the world, six Indigenous Quechua communities of the Peruvian Andes govern the Parque de la Papa (Potato Park) in Pisac, Cusco, a mountainous landscape that is one of the original homelands of the potato. They protect the region as a "biocultural heritage" territory, a trove of biological and cultural riches inherited from ancestors, and conserve more than 1,300 varieties of potato. When I visited in 2008 with other researchers and activists, I was stunned into silence by the diversity.

"This is the outcome of 20 years' consistent work in relocalizing our food system, from a time when we had become too dependent on outside agencies for our basic needs," farmer Mariano Sutta Apocusi told Local Futures, an organization dedicated to strengthening communities worldwide, in August 2020. "Focusing on the local has helped us improve access to and affordability of a great diversity of food products—especially native potatoes, quinoa, kiwicha, other Andean tubers and maize, which we cultivate using Indigenous agroecological methods." The communities instituted strong health and safety measures when the pandemic hit, even as they harvested a bumper crop and distributed more than a ton of potatoes to migrants, the elderly and a shelter for abused teenage mothers in Cusco town.

In Europe, many "solidarity economy" initiatives, which promote a culture of caring and sharing, swung into action when COVID-related lockdowns rendered massive numbers of people jobless. In Lisbon, Portugal, the social centers Disgraça and RDA69, which strive to re-create community life in an otherwise highly fragmented urban situation, reached out with free or cheap food to whoever needed it. They provided not only meals but also spaces where refugees, the homeless, unemployed young people and others who might otherwise have fallen through the cracks could interact with and develop relationships with better-off families, creating a social-security network of sorts. The organizers trusted those with adequate means to donate food or funds to the effort, strengthening the feeling of community in surrounding neighborhoods.

The pandemic has exposed the brittleness of a globalized econ-

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MOLIGERI CHANDRAMMA manages the DDS seed bank (*left*). It contains more than 70 species and varieties of crops. People gathered (*above*) in 2005 to mark 20 years of sustained protests against dam construction on the Narmada River.

omy that is advertised as benefiting everyone but in fact creates deep inequalities and insecurities. In India alone, 75 million people fell below the poverty line in 2020; globally, hundreds of millions who depend for their survival and livelihoods on the long-distance trade and exchange of goods and services were badly hit. Similar, albeit less extreme, dislocations also appeared during the 2008 financial crisis, when commodity speculation, along with the diversion of food grains to biofuel production, precipitated a steep rise in global grain prices, leading to hunger and food riots in many countries that depended on imported food. Threats to survival also emerge when war or other dislocations stop the movement of goods. In such crises, communities fare better if they have local markets and services and can provide their own food, energy and water while taking care of the less fortunate.

The value of these alternative ways of living goes far beyond their resilience during relatively short-term upheavals like the pandemic, however. As a researcher and environmental activist based in a "developing" country, I have long advocated that the worldviews of peoples who live close to nature be incorporated into global strategies for wildlife protection, such as at the International Union for Conservation of Nature and the United Nations' Convention on Biological Diversity. And in recent decades I have come to agree with critics of globalization such as social scientist and environmentalist Wolfgang Sachs who say that fending off calamities like biodiversity collapse will require not only environmental adaptations but also radical changes to the dominant economic, social and even political paradigms.

In 2014 a few of us in India initiated a process to explore pathways to a world in which people are at peace with one another and with nature. Five years later (and fortuitously, just before the pandemic hit), the endeavor grew into an international online network we called the Global Tapestry of Alternatives. These conversations and other research indicate that viable options, no matter where they are, tend to be based on self-reliance and solidarity.

Such values are at odds with globalization, which delivers to denizens of the Global North (the better off, no matter where we live) many things that we have come to regard as essential. In contrast to the promise of ever increasing material wealth that underpins our civilization, peoples who live near or beyond its margins have a multitude of visions for living well, each tailored to the specifics of their ecosystems and cultures. To walk away from the cliff edge of irreversible destabilization of the biosphere, I believe we must enable alternative structures, such as those of the Dalit farmers, the Quechua conservers and the Lisbon volunteers, to flourish and link up into a tapestry that ultimately covers the globe.

AN ENLIGHTENING JOURNEY

GROWING UP IN INDIA, where lifestyles that are intimately entwined with the natural environment survive in large pockets, unquestionably influenced my ideas of what constitutes true sustainability. In the 1970s, as a high school student who loved bird-

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watching in forests around Delhi, I joined classmates to demonstrate outside the Saudi Arabian embassy when some princes arrived in the country to hunt the (now critically endangered) Great Indian Bustard. Our protest, along with that of the Bishnoi community in Rajasthan, which traditionally protects these birds and other wildlife, embarrassed the Indian government into requesting that the hunters go home. Many of us went on to campaign for protection of the Delhi Ridge Forest, one of the world's biggest urban jungles. In 1979 we formed an environmental group to systematize our efforts. We called it Kalpavriksh, after a mythical tree that makes wishes come true; the name symbolized our growing awareness that nature gives us everything.

Our activism would teach us at least as much as we learned in school and college. While investigating the sources of Delhi's air pollution, for instance, we interviewed villagers who lived around a coal-fired power plant just outside the city. They turned out to be far worse affected by its dust and pollution than we city dwellers were—although they got none of its electricity. The benefits of the project flowed mainly to those who were already better off, whereas the disempowered experienced most of the harms.

In late 1980 we traveled to the western Himalayas to meet the protagonists of the iconic Chipko movement. Since 1973 village women had been protecting trees slated for logging by the forest department or by companies based in the Indian plains with their bodies. The deodars being felled, as well as the oaks, rhododendrons, and other species, were sacred, the women told us, as well as being essential for their survival. They provided cattle fodder, fertilizer and wild foods and sustained their water sources. Even as an urban student, I could see the central role that rural women played in protecting the environment—as well as the injustice of distant bureaucrats making decisions with little concern for how they impacted those on the ground.

Soon after, my friends and I learned that 30 major dams were to be constructed on the Narmada River basin in central India. Millions worshipped the Narmada as a tempestuous but bountiful goddess—so pristine that the Ganga is believed to visit her every year to wash away her sins. Trekking, boating and riding buses along its length of 1,300 kilometers, we were dazzled by waterfalls plunging into spectacular gorges, densely forested slopes teeming with wildlife, fields of diverse crops, thriving villages and ancient temples, all of which would be drowned. We began to question the concept of development itself. Surely the destruction would far outweigh any possible benefits? Almost four decades later our fears have proved tragically true. Hundreds of thousands of displaced people still await proper rehabilitation, and the river downstream of the dams has become a trickle—enabling seawater to reach 100 kilometers inland.

Over the years I came to understand how powerful economic forces reach around the globe to intimately link social injustice with ecological destruction. The era of colonization and slavery vastly expanded the economic and military reach of some nation-states and their allied corporations, enabling the worldwide extraction of natural resources and exploitation of labor to feed the emerging industrial revolution in Europe and North America. Economic historians, anthropologists and others have demonstrated how this painful history laid the foundation of today's

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PARQUE DE LA PAPA (*left*) in Peru is one of the original homelands of the potato. The Quechua Indigenous people (*center*) govern the region as a "biocultural heritage" territory, conserving a remarkable diversity of potatoes (*right*).

global economy. Apart from driving irreversible ecological damage, this economic system robs many communities of access to the commons—to rivers, meadows and forests essential for their survival—while creating a dependence on external markets. The massive suffering during the pandemic has merely exposed these historical and contemporary fault lines.

During my wanderings over the decades and especially while researching a book with economist Aseem Shrivastava, I became aware of a far more hopeful trend. Across the country and indeed around the world, hundreds of social movements are empowering the marginalized to wrest back control over their lives and livelihoods. In 2014 Kalpavriksh initiated a series of gatherings called Vikalp Sangam, or Confluence of Alternatives, where the drivers of these spirited efforts could come together, share ideas and experiences, and collaborate, helping to build a critical mass for change.

These interactions and eclectic reading gave me insights into a vital question I was investigating: What are the essential characteristics of desirable and viable alternatives? Happily, I was far from alone in this quest. At a degrowth conference in Leipzig in 2014, I was excited to hear Alberto Acosta, an economist and former politician from Ecuador, speaking on *buen vivir,* an Indigenous worldview founded on living well with one another and with the rest of nature. Although Acosta spoke no English and I spoke no Spanish, we tried excitedly to converse; subsequently, degrowth expert Federico Demario joined us and helped to translate. We decided to work on a compilation of thriving alternatives from around the world, jotting down 20 possible ideas on the back of an envelope. Later we roped in development critic Arturo Escobar and ecofeminist Ariel Salleh as co-editors of a volume we called *Pluriverse*. The number of entries expanded to more than 100.

COMMONALITIES

THOUGH DAZZLINGLY DIVERSE, the alternatives emerging worldwide share certain core principles. The most important is sustaining or reviving community governance of the commons—of land, ecosystems, seeds, water and knowledge. In 12th-century England, powerful people began fencing off, or "enclosing," fields, meadows, forests and streams that had hitherto been used by all. Enclosures by landlords and industrialists expanded to Europe and accelerated with the industrial revolution, forcing tens of millions of dispossessed people to either become factory workers or emigrate to the New World, devastating native populations. Imperial nations seized large portions of continents and reconfigured the economies of the colonies, extracting raw materials for factories, capturing markets for exports of manufactured goods and obtaining foods such as wheat, sugar and tea for the newly created working class. In this way, colonizers and their allies established a system of perpetual economic domination that generated the Global North and the Global South (the world of the marginalized, no matter where they live).

The wave of anticolonial movements in the first few decades of the 20th century, many of them successful, sparked fears that supplies of raw materials for industries and markets for finished goods of higher value would dry up. President Harry S. Truman responded by launching a program for alleviating poverty in what he described as "underdeveloped areas" with their "primitive and stagnant" economies. As detailed by ecologist Debal Deb, newly formed financial institutions controlled by the rich countries helped the ex-colonies "develop" along the path blazed by the West, providing the materials and energy sources for and creating markets for cars, refrigerators and other consumer goods. An integral aspect of development, as thus conceived, propagated and usually enforced

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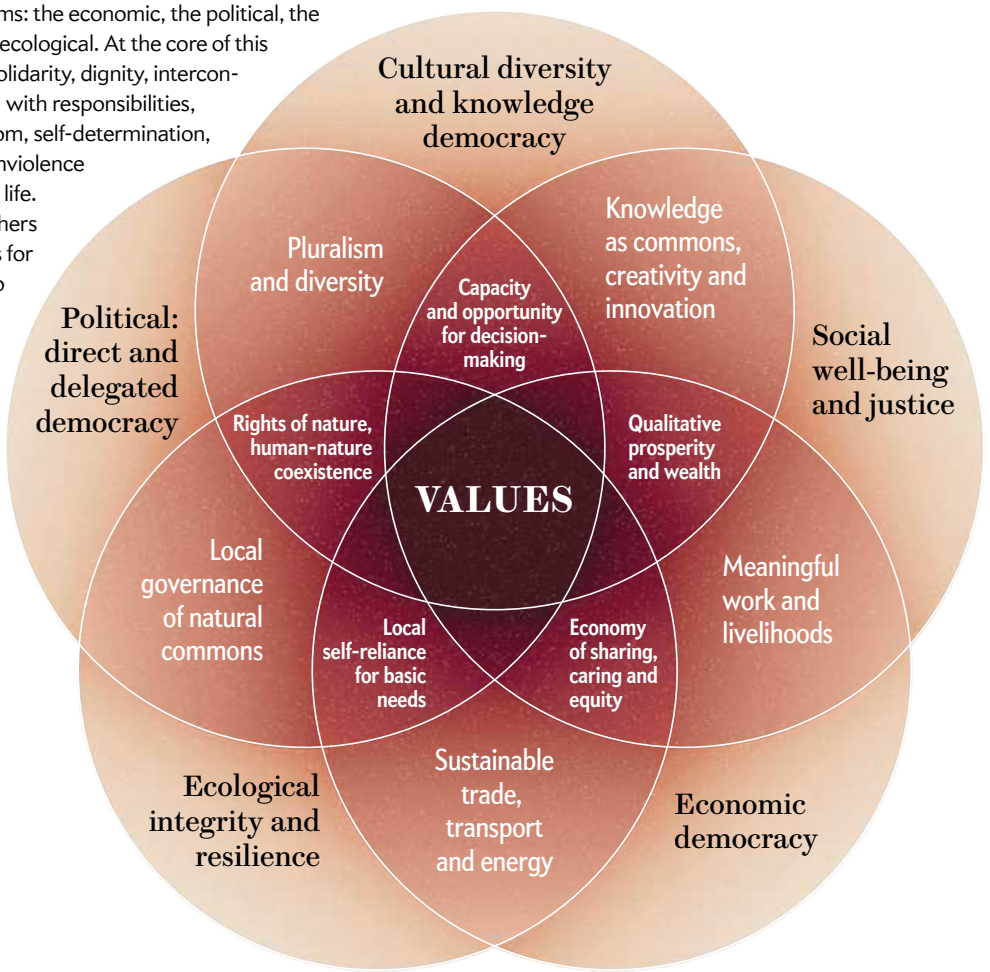
Spheres of Transformation

Creating a sustainable and equitable world will require metamorphoses in five intersecting realms: the economic, the political, the social, the cultural and the ecological. At the core of this flower are values such as solidarity, dignity, interconnectedness, rights coupled with responsibilities, diversity, autonomy, freedom, self-determination, self-reliance, simplicity, nonviolence and respect for all forms of life. Indigenous peoples and others have lived by similar values for centuries, and they are also being embraced and asserted by people in industrial societies as solutions to global ecological and social crises.


Cultural diversity and knowledge democracy
Pluralism and diversity
Knowledge as commons, creativity and innovation
Political: direct and delegated democracy
Capacity and opportunity for decision-making
Social well-being and justice
Rights of nature, human-nature coexistence
Qualitative prosperity and wealth
VALUES
Local governance of natural commons
Meaningful work and livelihoods
Local self-reliance for basic needs
Economy of sharing, caring and equity
Ecological integrity and resilience
Sustainable trade, transport and energy
Economic democracy

by stringent conditions attached to loans from the World Bank and the International Monetary Fund, has been privatization or state confiscation of the commons to extract metals, oil and water.

As Elinor Ostrom, winner of the 2009 Nobel Memorial Prize in Economic Sciences, demonstrated, however, the commons are far more sustainably governed by the communities from which they are wrested than by the governments or corporations that claim them. This awareness has given rise to innumerable grassroots efforts to protect the surviving commons and reestablish control over others. What constitutes the commons has also expanded to include "physical and knowledge resources that we all share for everyone's benefit," explains sociologist Ana Margarida Esteves, who helps with the European Commons Assembly, an umbrella organization for hundreds of such endeavors.

Many of the efforts resemble the DDS and the Parque de la Papa in using community governance of commonly held resources to enhance agroecology (smallholder farming that sustains soil, water and biodiversity) and food sovereignty (control over all means of food production, including land, soil, seeds and the knowledge of how to use them). The food-sovereignty movement La Via Campesina, which originated in Brazil in 1993, now includes about 200 million farmers in 81 countries. Such attempts at self-reliance and community governance extend also to other basic needs, such as for energy and water. In Costa Rica, Spain and Italy, rural cooperatives have been generating electricity locally and controlling its distribution since the 1990s. And hundreds of villages in western India have moved toward "water democracy," based on decentralized harvesting of water and community management of wetlands and groundwater. Mobilizing people to sustain, build or rebuild local systems of knowledge is essential to such ventures.

Secure rights to govern the commons are also important. In the Ecuadorian Amazon, the Sapara Indigenous people fought hard to gain collective rights over their rain-forest home. They are now defending it against oil and mining interests while developing a model of economic well-being that blends their traditional cosmovisions—ways of knowing, being and doing that are physically and spiritually linked to their environs—with new activities such as community-led ecotourism. Their income from

Source: "Alternatives Transformation Format: A Process for Self-Assessment and Facilitation towards Radical Change," prepared by Kalpavriksh for ACKnowl-EJ (*chart reference*)

Graphic by Federica Fragapane

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tourism has dropped during the pandemic, but their forests and community ethic give them almost all the food, water, energy, housing, medicines, enjoyment, health and learning that they need. They are now offering online sessions on their cosmovisions, dream analysis and healing. I participated in such sessions in person in their Naku ecotourism camp in 2019. The virtual version is not as immersive but nonetheless represents an innovative adaptation to the circumstances.

Greening cities or making them more welcoming, as the Lisbon social centers do, also requires community-based governance and economies of caring and sharing. Across the Global South, development projects have driven hundreds of millions of people to cities, where they live in slums and work in hazardous conditions. Wealthy city dwellers could do their part by consuming less, which would reduce the extraction and waste dumping that displace people in faraway places. A spectrum of avenues toward more equitable and sustainable cities has emerged. These include, for example, the Transition Movement, which is attempting to regenerate the commons and make European cities carbon-neutral, and the municipalism movement, which is creating a network of Fearless Cities, among them Barcelona, Valparaiso, Madrid and Athens, to provide secure environments for refugees and migrants. Urban agriculture in Havana supplies more than half of its fresh food requirements and has inspired many other city farming initiatives around the world.

FIVE PETALS

THESE INITIATIVES POINT TO the need for fundamental transformations in five interconnected realms. In the *economic sphere,* we need to get away from the development paradigm—including the notion that economic growth, as measured by gross domestic product (GDP), is the best means of achieving human goals. In its place, we need systems for respecting ecological limits, emphasizing well-being in all its dimensions and localizing exchanges to enable self-reliance—as well as good measures of these indicators. Bhutan has long experimented with gross national happiness as an index; the idea has spawned variants, such as New Zealand's recent focus on mental health and other such measures of progress.

We also need freedom from centralized monetary and financial control. Many experiments in alternative currencies and economies based on trust and local exchanges are underway. Perhaps the most innovative of these is "time banking," a system for swapping services founded on the principle that all skills or occupations merit equal respect. One can, for example, give a one-hour-long yoga lesson for credit that can be redeemed for an hour's work on bicycle repair. In many parts of the world, workers are seeking to control the means of production: land, nature, knowledge and tools. A few years back I visited Vio.Me, a detergent factory in Thessaloniki, Greece, which workers had taken over and converted from chemical to olive-oil-based and eco-friendly production, and where they had established complete parity in pay, regardless of what job the worker was doing. The slogan on their wall proclaimed: "We have no boss!"

In fact, work itself is being redefined. Globalized modernity has created a chasm between work and leisure—which is why we wait desperately for the weekend! Many movements seek to bridge this gap, enabling greater enjoyment, creativity and satisfaction. In industrial countries, people are bringing back manual ways of making clothes, footwear or processed foods under banners such as "The future is handmade!" In western India, many young people are leaving soul-killing routines in factories to

WORKERS such as Dimitris Koumatsioulis (*top*) collectively run Vio.Me, an eco-friendly detergent factory in Thessaloniki, Greece. In Prague, Czech Republic, people buy and sell locally (*bottom*) at a farmers' and producers' market.

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KUZGUNCUK BOSTAN, an urban commons in Istanbul, Turkey, enables city dwellers to collectively grow their own fruit, vegetables and other produce.

return to handloom weaving, which allows them to control their schedules while providing a creative outlet.

In the *political sphere,* the centralization of power inherent in the nation-state, whether democratic or authoritarian, disempowers many peoples. The Sapara nation in Ecuador and the Adivasis of central India argue for a more direct democracy, where power resides primarily with the community. The state—insofar as it continues to exist—would then mainly help with larger-scale coordination while being strictly accountable to decision-making units on the ground. The ancient Indian notion of *swaraj,* literally translated as "self-rule," is particularly relevant here. It emphasizes individual and collective autonomy and freedom that are linked to responsibility for others' autonomy and freedom. A community that practices *swaraj* may not dam a stream, for example, if that threatens the water supply of downstream villages; its well-being cannot compromise that of others.

Such a notion of democracy also challenges the boundaries of nation-states, many of which are products of colonial history and have ruptured ecologically and culturally contiguous areas. The Kurdish people, for instance, are split among Turkey, Iran, Iraq and Syria. For three decades they have struggled to achieve autonomy and direct democracy based on principles of ecological sustainability and women's liberation—and without borders dividing them. And Indigenous groups in Mexico collectively identifying as Zapatistas have for more than three decades asserted and sustained an autonomous region based on similar principles.

Moving toward such radical democracy would suggest a world with far fewer borders, weaving tens of thousands of relatively autonomous and self-reliant communities into a tapestry of alternatives. These societies would connect with one another through "horizontal" networks of equitable and respectful exchange, as well as through "vertical" but downwardly accountable institutions that manage processes and activities across the landscape.

Several experiments in bioregionalism at large scales are underway, although most remain somewhat top-down in their governance. In Australia, the Great Eastern Ranges Initiative seeks to coordinate the conservation of ecosystems across 3,600 kilometers while sustaining livelihoods and community health. And a project spanning six countries aims to conserve as a World Heritage Site the Qhapaq Ñan, a 30,000-kilometer network of roads in the Andes built by the Inca Empire, along with its related cultural, historical and environmental heritage.

Local self-governance may, of course, be oppressive or exclusionary. The intensely patriarchal and casteist traditional village councils in many parts of India and the xenophobic antirefugee approaches of the right wing in Europe illustrate this drawback. A third crucial sphere of transformation is therefore *social justice,* encompassing struggles against racism, casteism, patriarchy, and other traditional or modern forms of discrimination and exploitation. Fortunately, success in defying the dominant economic system often goes hand in hand with victories against discrimination, such as Dalit women farmers' shaking off centuries of caste and patriarchal oppression to achieve food sovereignty.

Political autonomy and economic self-reliance need not mean isolationism and xenophobia. Rather cultural and material exchanges that maintain local self-reliance and respect ecological sustainability would replace present-day globalization—which

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perversely allows goods and finances to flow freely but stops desperate humans at borders. This kind of localization would be open to people in need; refugees from climate change or war would be welcomed, as in the network of Fearless Cities in Europe. Both grounded practice and shifts in policy could help transit toward such a system. Necessary, of course, are attempts to rebuild societies in regions of strife so that people do not have to flee from them.

Radical change also necessitates transformations in a fourth sphere: that of *culture and knowledge.* Globalization devalues languages, cultures and knowledge systems that do not adapt to development. Several movements are confronting this homogenizing tendency. The Sapara nation is trying to resuscitate its almost extinct language and preserve its knowledge of the forest by bringing these into the curriculum of the local school, for instance. Many communities are "decolonizing" maps, putting back their own place names and defying political borders. Even the colonial-era Mercator projection used to generate the familiar world map is being upended. (Only recently did I realize that Africa is large enough to contain Europe, China, the U.S. and India put together.) Increasingly, traditional and modern sciences are collaborating to help solve humankind's most vexing problems. The Arctic Biodiversity Assessment, for example, involves cooperation among Indigenous peoples and university scientists to tackle climate change.

One problem is that present-day educational institutions train graduates who are equipped to serve and perpetuate the dominant economic system. People are bringing community and nature back into spaces of learning, however. These efforts include forest schools in many parts of Europe that provide children with hands-on learning in the midst of nature, the Zapatista autonomous schools that teach about diverse cultures and struggles, and the Ecoversities Alliance of centers of higher learning around the world that enable scholars to seek knowledge across the boundaries that typically separate academic disciplines.

The most important sphere of transformation, however, is the *ecological*—recognizing that we are part of nature and that other species are worthy of respect in their own right. Across the Global South, communities are leading efforts to regenerate degraded ecosystems and wildlife populations and conserve biodiversity. Tens of thousands of "territories of life" are being governed by Indigenous or other local communities, for example. These include locally managed marine areas in the South Pacific, Indigenous territories in Latin America and Australia, community forests in South Asia, and the Ancestral Domain territories in the Philippines. Also noteworthy is recent legislation or court judgments in several countries asserting that rivers, for example, enjoy the same protections as people. The United Nations' 2009 Declaration on Harmony with Nature is an important milestone toward such a goal.

VALUES

I AM OFTEN ASKED how one scales up successful alternatives. It would be self-defeating, however, to try to either scale up or replicate a DDS or a Parque de la Papa. The essence of this approach is diversity: the recognition that every situation is different. What people can do—and this, indeed, is how successful initiatives spread—is understand the underlying values and apply these in their own communities while networking with like ventures to spread the impact.

The Vikalp Sangam process has identified the following values as crucial: solidarity, dignity, interconnectedness, rights and responsibilities, diversity, autonomy and freedom, self-reliance and self-determination, simplicity, nonviolence and respect for all life. Around the world both ancient and modern worldviews that are focused on life articulate similar principles. Indigenous peoples and other local communities have lived by worldviews such as *buen vivir, swaraj, ubuntu* (an African philosophy that sees the well-being of all living things as interconnected) and many other such ethical systems for centuries and are reasserting them. Simultaneously, approaches such as degrowth and ecofeminism have emerged from within industrial societies, seeding powerful countercultures.

At the heart of these worldviews lies a simple principle: that we are all holders of power. That in the exercise of this power, we not only assert our own autonomy and freedom but also are responsible for ensuring the autonomy of others. Such a *swaraj* merges with ecological sustainability to create an eco-*swaraj,* encompassing respect for all life.

Clearly, such fundamental transformations face a deeply entrenched status quo that retaliates violently wherever it perceives a threat. Hundreds of environmental defenders are murdered every year. Another serious challenge is the unfamiliarity many people in the Global North have with ideals of a good life beyond the American dream. Even so, the fact that many progressive initiatives are thriving and new ones are sprouting suggests that a combination of resistance and constructive alternatives does stand a chance.

The COVID pandemic is a catastrophe that presents humankind with a choice. Will we head right back toward some semblance of the old normal, or will we adopt new pathways out of global ecological and social crises? To maximize the likelihood of the latter, we need to go well beyond the Green New Deal approaches in the U.S., Europe, and elsewhere. Their intense focus on the climate crisis and worker rights is valuable, but we also need to challenge unsustainable consumption patterns, glaring inequalities and the need for centralized nation-states.

Truly life-sustaining recoveries would emphasize all the spheres of eco-*swaraj,* arrived at via four pathways. One is the creation or revival of dignified, secure and self-reliant livelihoods for two billion people based on collective governance of natural resources and small-scale production processes such as farming, fisheries, crafts, manufacturing and services. Another is a program for regeneration and conservation of ecosystems, led by Indigenous peoples and local communities. A third is immediate public investments in health, education, transportation, housing, energy and other basic needs, planned and delivered by local democratic governance. Finally, incentives and disincentives to make production and consumption patterns sustainable are crucial. These approaches would integrate sustainability, equality and diversity, giving everyone, especially the most marginalized, a voice. A proposal for a million climate jobs in South Africa is of this nature, as is a feminist economic recovery plan for Hawaii and several other proposals for social justice in other countries.

None of this will be easy, but I believe it is essential if we are to make peace with Earth and among ourselves. SA

Ashish Kothari is a founding member of Kalpavriksh, an environmental organization in India. He helps coordinate the Global Tapestry of Alternatives and has co-authored or co-edited several books, including *Churning the Earth* (2012) and *Pluriverse* (2019).

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OUR DIGITAL DOUBLES

AI will serve our species, not control it

By Pedro Domingos

Illustration by Armando Veve

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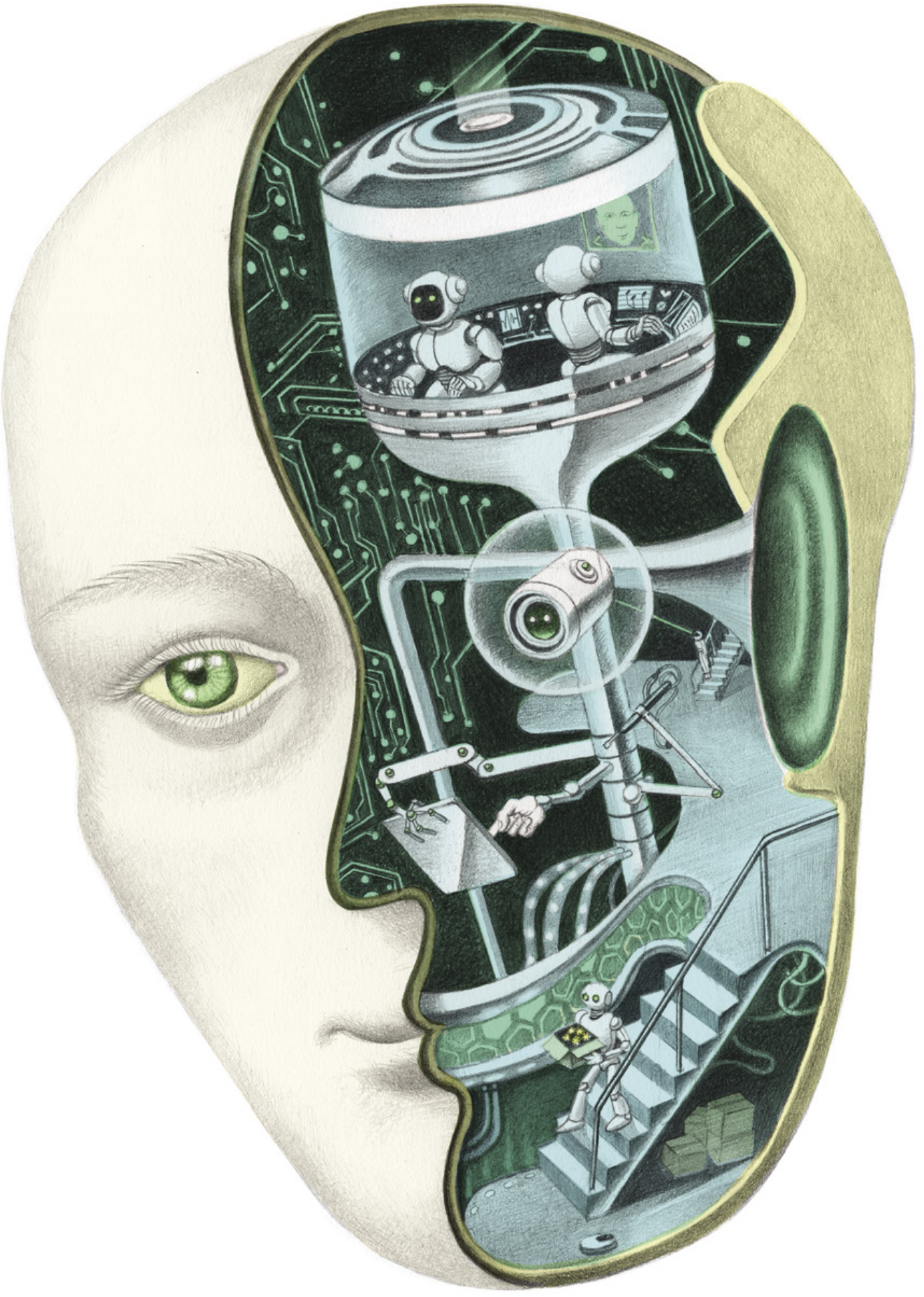

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HUMANS ARE THE ONLY ANIMALS THAT BUILD MACHINES. By doing so, we expand our capabilities beyond our biological limits. Tools turn our hands into more versatile appendages. Cars let us travel faster, and airplanes give us wings. Computers endow us with bigger brains and memory capacity, and smartphones orchestrate daily life. Now we are creating technology that can evolve on its own by encoding into it an ability to learn through data and effort. Will it ultimately supplant us? Or will it augment our abilities, enhancing our humanness in unprecedented ways?

Machine learning started in the 1950s with the work of pioneering scientists such as Frank Rosenblatt, who built an electronic neuron that learned to recognize digits, and Arthur Samuel, whose checkers program learned by playing against itself until it could beat some humans. But it is only in the past decade that the field has truly taken off, giving us self-driving cars, virtual assistants that understand our commands (up to a point) and countless other applications.

Every year we invent thousands of new algorithms, which are sequences of instructions telling a computer what to do. The hallmark of learning machines, however, is that instead of programming them in detail, we give them general goals such as "learn to play checkers." Then, like humans, they improve with experience. These learning algorithms tend to fall into five main categories, each inspired by a different scientific field. Unsurprisingly, one way that machines learn is by mimicking natural selection, through evolutionary algorithms. In the Creative Machines Lab at Columbia University, primitive robots try to crawl or fly, and the specifications of those that perform best are periodically mixed and mutated to 3-D print the next generation. Starting with randomly assembled bots that can barely move, this process eventually produces creatures such as robot spiders and dragonflies after thousands or tens of thousands of generations.

But evolution is slow. Deep learning, currently the most popular machine-learning paradigm, takes inspiration from the brain. We start with a highly simplified mathematical model of how a neuron works and then build a network from thousands or millions of these units and let it learn by gradually strengthening the connections between neurons that fire together when looking at data. These neural networks can recognize faces, understand speech and translate languages with uncanny accuracy. Machine learning also draws on psychology. Like humans, these analogy-based algorithms solve new problems by finding similar ones in memory. This ability allows for the automation of customer support, as well as e-commerce sites that recommend products based on your tastes.

Machines may also learn by automating the scientific method. To induce a new hypothesis, symbolic learners invert the process of deduction: If I know that Socrates is human, what else do I need to infer that he is mortal? Knowing that humans are mortal would suffice, and this hypothesis can then be tested by checking if other humans in the data are also mortal. Eve, a biologist robot at Chalmers University of Technology in Sweden, has used this approach to discover a potential new malaria drug. Starting with data about the disease and basic knowledge of molecular biology, Eve formulated hypotheses about what drug compounds might work, designed experiments to test them, carried out the experiments in a robotic lab, revised or discarded the hypotheses, and repeated until it was satisfied.

Finally, learning can rely purely on mathematical

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principles, the most important of which is Bayes's theorem. The theorem says that we should assign initial probabilities to hypotheses based on our knowledge, then let the hypotheses that are consistent with the data become more probable and those that are not become less so. It then makes predictions by letting all the hypotheses vote, with the more probable ones carrying more weight. Bayesian learning machines can do some medical diagnoses more accurately than human doctors. They are also at the heart of many spam filters and of the system that Google uses to choose which ads to show you.

Each of these five kinds of machine learning has its strengths and weaknesses. Deep learning, for example, is good for perceptual problems such as vision and speech recognition but not for cognitive ones such as acquiring commonsense knowledge and reasoning. With symbolic learning, the reverse is true. Evolutionary algorithms are capable of solving harder problems than neural networks, but it can take a very long time to solve them. Analogical methods can learn from just a small number of instances but are liable to get confused when given too much information about each. Bayesian learning is most useful for dealing with small amounts of data but can be prohibitively expensive with big data.

These vexing trade-offs are why machine-learning researchers are working toward combining the best elements of all the paradigms. In the same way that a master key opens all locks, our goal is to create a so-called master algorithm—one that can learn everything that can be extracted from data, deriving all possible knowledge from it.

The challenge on us now is similar to the one faced by physicists: quantum mechanics is effective at describing the universe at the smallest scales and general relativity at the largest scales, but the two are incompatible and need to be reconciled. And in the same way that James Clerk Maxwell first unified light, electricity and magnetism before the Standard Model of particle physics could be developed, different research groups, including mine at the University of Washington, have proposed ways to unify two or more of the machine-learning paradigms. Because scientific progress is not linear and instead happens in fits and starts, it is difficult to predict when the full unification of the master algorithm might be complete. Regardless, achieving this goal will not usher in a new, dominant race of machines. Rather it will accelerate human progress.

MACHINE TAKEOVER?

ONCE WE ATTAIN THE MASTER ALGORITHM and feed it the vast quantities of data each of us produce, artificial-intelligence systems will potentially be able to learn very accurate and detailed models of individual people: our tastes and habits, strengths and weaknesses, memories and aspirations, beliefs and personalities, the people and things we care about, and how we will respond in any given situation. That models of us could essentially predict the choices we will make is both exciting and disquieting.

Many worry that machines with these capabilities will use their newfound knowledge to take all our jobs, enslave us or even exterminate us. But that is unlikely to happen because they have no will of their own. Essentially all AI algorithms are driven by goals that we program, such as "find the shortest route from the hotel to the airport." What distinguishes these algorithms from ordinary ones is that they have a lot of flexibility in figuring out how to reach the goals we set for them rather than needing to execute a predefined series of steps. Even as they get better at the task with experience, the goals remain unchanged. Solutions that do not make progress toward the goal are automatically discarded. Plus, humans get to check that what the machines produce does indeed satisfy our objectives. We are also able to verify that the machines do not violate any of the constraints we put on them, such as "obey the rules of the road."

When we envision an AI, though, we tend to project onto it human qualities such as volition and consciousness. Most of us are also more familiar with humanlike AIs, such as home robots, than with the myriad other types that do their work behind the scenes. Hollywood compounds this perception by depicting robots and AIs as humans in disguise—an understandable tactic that makes for a more compelling story. Artificial intelligence is just the ability to solve hard problems—a task that does not require free will. It is no more likely to turn against us than your hand is to slap you. Like any other technology, AIs will always be extensions of us. The more powerful we can make them, the better.

What, then, might our AI-enabled future look like? Intelligent machines will indeed supplant many jobs, but the effects on society will likely be similar to previous forms of automation. Two hundred years ago the majority of Americans were farmers. Yet today machines have replaced almost all of them without causing massive unemployment. Doomsayers argue that this time is different because machines are replacing our brains, not just our brawn, leaving nothing for humans to do. But the day that AIs can carry out all the tasks we can is still very distant, if it ever comes. For the foreseeable future, AIs and humans will be good at different things. Machine learning's primary effect will be to greatly lower the cost of intelligence. This democratization will increase the variety of economically feasible uses of that intelligence, generating new jobs and transforming old ones to accomplish more with the same amount of human labor.

Then there is the "singularity" scenario, popularized by futurist Ray Kurzweil. It is one of ever accelerating technological progress: machines learn to make better machines, which in turn make even bet-

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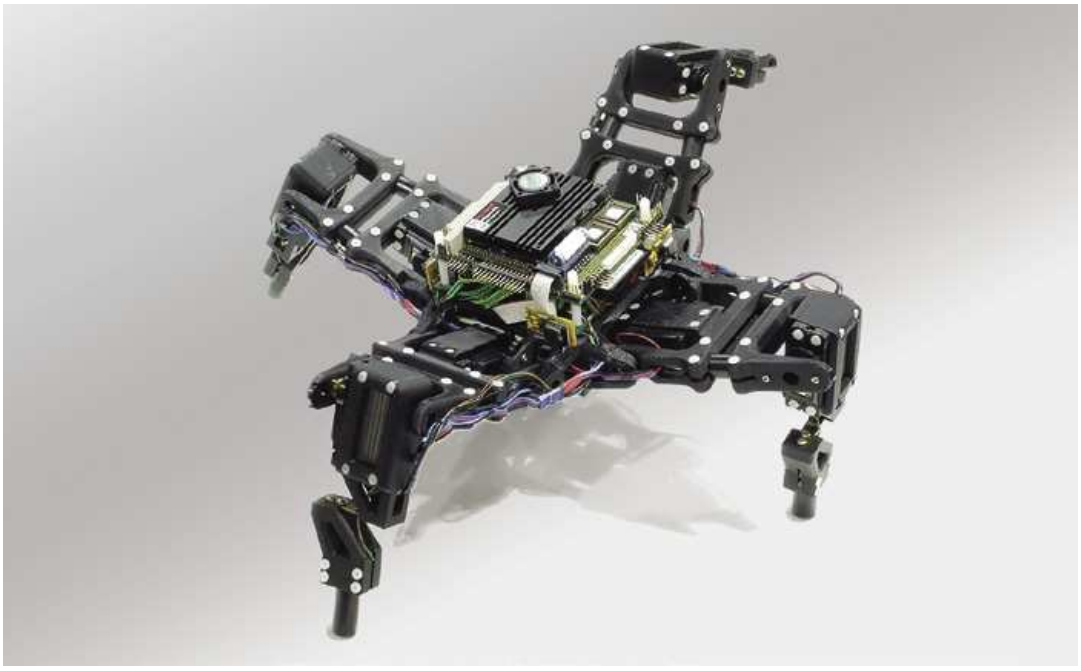

SMART BOT: This "sea star" robot uses evolutionary algorithms to learn how to simulate itself. These algorithms are one type of machine learning that could be unified with others into a "master algorithm," a singularly powerful human tool.

ter ones, and so on. But we know that this cannot continue forever because the laws of physics place strict limits on how powerful even a quantum computer can be, and in some aspects, we are not far from hitting them. The progress of AI, like the progress of everything else, will eventually plateau.

Another vision popular among futurists is that computer models of us will become so good that they will be practically indistinguishable from the real thing. In this scenario, we could upload ourselves to the cloud and live on forever as pieces of software, free of the pesky constraints of the physical world. One problem with this scenario is that it may not be biologically feasible. To upload yourself, you would presumably need an accurate model of each of your neurons, complete with the memories they store. It would have to be captured so reliably that the model's predictions would not rapidly diverge from the behavior of the real neurons—a tall order indeed.

But even if this were a realistic option, would you really upload yourself if you had the chance? How could you know for sure that your model was not missing some essential part of you—or that it was conscious at all? What if a thief stole your identity in the most absolute and complete sense of the word? I believe that people will opt to hang on to their squishy, carbon-based selves—the "wetware," as computer scientists jokingly call it—for as long as they can and then call it quits.

CHERCHEZ L'HUMAIN

AI—MACHINE LEARNING IN PARTICULAR—is really just the continuation of human evolution. In *The Extended Phenotype,* Richard Dawkins shows how common it is for animals' genes to control the environment beyond their bodies, from cuckoo eggs to beaver dams. Technology is the extended phenotype of humans, and what we are building today is another layer of our technological exoskeleton. I think the most likely scenario for how humans will use AI is more fascinating than the usual speculations.

Within a decade or so each one of us will probably have a "digital double," an AI companion that will be even more indispensable than our smartphones are today. Your digital double will not need to physically move around with you; most likely it will live somewhere in the cloud, just as much of your data already does. We can see its beginnings in virtual assistants such as Siri, Alexa and Google Assistant. At the heart of your digital double will be a model of you, learned from all the data you have ever generated in your interactions with the digital world, from desktop computers and Web sites to wearable devices and sensors in the environment such as smart speakers, thermostats, cell-phone towers and video cameras.

The better our learning algorithms become and the more personal data we feed them, the more accurate our digital doubles will get. Once we have the master algorithm and then couple it with continuous capture of your sensorimotor stream via an augmented-reality headset and other personal sensors, your double will grow to know you better than your best friend.

The model and data will be maintained by a "data bank," not unlike a traditional bank that stores and invests your money. Many existing companies would surely like to provide that service for you. Google cofounder Sergey Brin has said that Google wants to be "the third half of your brain," but you probably would

Victor Zykov and Josh Bongard

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not want part of your brain to subsist by showing you ads. You might be better served by a new kind of company with fewer conflicts of interest or by a data union you form with like-minded people.

After all, the central worry about AI is not that it will spontaneously turn evil but that the humans who control it will misuse it (*cherchez l'humain,* as the French might say—"look to the human"). So your data bank's first duty will be to ensure that your model is never used against your interests. Both you and the data bank must be vigilant about monitoring AI crime because this technology will empower bad actors as much as anyone. We will need AI police (the Turing police, as William Gibson called it in his 1984 book *Neuromancer*) to catch the AI criminals.

If you have the misfortune of living under an authoritarian regime, this scenario could usher in unprecedented dangers because it will allow the government to monitor and restrain you like never before. Given the speed at which machine learning is progressing and the predictive policing systems already in use, the *Minority Report* scenario—where people are preemptively arrested when they are about to commit a crime—no longer seems farfetched. Then there are the implications of inequality as the world adapts to the speed of life with digital doubles before all of us are able to afford one.

Our first duty, as individuals, will be not to become complacent and trust our digital doubles beyond their years. From the outside, AIs may seem objective, even perfect, but inside they are as flawed as we are or more, just in different ways. For example, AIs lack common sense and can easily make errors that a human never would, such as mistaking a person crossing the street for a windblown plastic bag. They are also liable to take our instructions too literally, giving us precisely what we asked for instead of what we actually wanted. (So think twice before telling your self-driving car to get you to the airport on time at all costs.)

Practically speaking, your digital double will be similar enough to you to take your place in all kinds of virtual interactions. Its job will not be to live your life for you but rather to make all the choices you do not have the time, patience or knowledge for. It will read every book on Amazon and recommend the few that you are most likely to want to read yourself. If you need a car, it will research the options and haggle with the car dealer's bots. If you are job hunting, it will interview itself for all the positions that fit your needs and then schedule live interviews for you for the most promising ones. If you get a cancer diagnosis, it will try all potential treatments and recommend the most effective ones. (It will be your ethical duty to use your digital double for the greater good by letting it take part in medical research, too.) And if you are seeking a romantic partner, your double will go on millions of virtual dates with all eligible doubles. The pairs that hit it off in cyberspace can then go on a date in real life.

Your digital double will take your place in all kinds of virtual interactions.

Essentially your double will live out countless probable lives in cyberspace so that the single one you live in the physical world is likely to be the best version. Whether your simulated lives are somehow "real" and your cyberselves have a kind of consciousness (as portrayed in the plots of some *Black Mirror* episodes, for instance) are interesting philosophical questions.

Some people worry that this means that we are handing over control of our lives to computers. But it actually gives us more control, not less, because it allows us to make choices we could not before. Your model will also learn from the results of each virtual experience (Did you enjoy the date? Do you like your new job?) so that over time, it will become better at suggesting the things you would choose for yourself.

In fact, we are already accustomed to most of our decision-making taking place without our conscious intervention because that is what our brains do now. Your digital double will be like a greatly expanded subconscious, with one key difference: Whereas your subconscious lives alone inside your skull, your digital double will continuously interact with those of other people and organizations. Everyone's doubles will keep trying to learn models of one another, and they will form a society of models, living at computer speeds, branching out in all directions, figuring out what we would do if we were there.

Our machines will be our scouts, blazing a trail into the future for us as individuals and as a species. Where will they lead us? And where will we choose to go? SA

Pedro Domingos is a professor of computer science at the University of Washington and author of *The Master Algorithm* (Basic Books, 2015). A fellow of the Association for the Advancement of Artificial Intelligence, he lives near Seattle.

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BREAK DOWN SILOS

Solving today's complex, global problems will take interdisciplinary science

By Graham A. J. Worthy and Cherie L. Yestrebsky

Illustration by Neil Webb

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THE INDIAN RIVER LAGOON, A SHALLOW ESTUARY THAT stretches for 156 miles along Florida's eastern coast, is suffering from the activities of human society. Poor water quality and toxic algal blooms have resulted in fish kills, manatee and dolphin die-offs and takeovers by invasive species. But the humans who live here have needs, too: the eastern side of the lagoon is buffered by a stretch of barrier islands that are critical to Florida's economy, tourism and agriculture, as well as for launching NASA missions into space.

As in Florida, many of the world's coastlines are in serious trouble as a result of population growth and the pollution it produces. Moreover, the effects of climate change are accelerating both environmental and economic decline. Given what is at risk, scientists like us—a biologist and a chemist at the University of Central Florida—feel an urgent need to do research that can inform policy that will increase the resiliency and sustainability of coastal communities. How can our research best help balance environmental and social needs within the confines of our political and economic systems? This is the level of complexity that scientists must enter into instead of shying away from.

Although new technologies will surely play a role in tackling issues such as climate change, rising seas and coastal flooding, we cannot rely on innovation alone. Technology generally does not take into consideration the complex interactions between people and the environment. That is why coming up with solutions will require scientists to engage in an interdisciplinary team approach—something that is common in the business world but is relatively rare in universities.

Universities are a tremendous source of intellectual power, of course. But students and faculty are typically organized within departments, or academic silos. Scientists are trained in the tools and language of their respective disciplines and learn to communicate their findings to one another using specific jargon.

When the goal of research is a fundamental understanding of a physical or biological system within a niche community, this setup makes a lot of sense. But when the problem the research is trying to solve extends beyond a closed system and includes its effects on society, silos create a variety of barriers. They can limit creativity, flexibility and nimbleness and actually discourage scientists from working across disciplines. As professors, we tend to train our students in our own image, inadvertently producing specialists who have difficulty communicating with the scientist in the next building—let alone with the broader public. This makes research silos ineffective at responding to developing issues in policy and planning, such as how coastal communities and ecosystems worldwide will adapt to rising seas.

SCIENCE FOR THE BIGGER PICTURE

AS SCIENTISTS WHO LIVE and work in Florida, we realized that we needed to play a bigger role in helping our state—and country—make evidence-based choices when it comes to vulnerable coastlines. We wanted to make a more comprehensive assessment of both natural and human-related impacts to the health, restoration and sustainability of our coastal systems and to conduct long-term, integrated research.

At first, we focused on expanding research capacity in our biology, chemistry and engineering programs because each already had a strong coastal research presence. Then, our university announced a Faculty Cluster Initiative, with a goal of developing interdisciplinary academic teams focused on solving tomorrow's most challenging societal problems. While putting together our proposal, we discovered that there were already 35 faculty members on the Orlando campus who studied coastal issues. They belonged to 12 departments in seven colleges, and many of them had never even met. It became clear that simply working on the same campus was insufficient for collaboration.

So we set out to build a team of people from a wide mix of backgrounds who would work in close proximity to one another on a daily basis. These core members would also serve as a link to the disciplinary strengths of their tenure home departments. Initially, finding experts who truly wanted to embrace the team aspect was more difficult than we thought. Although the notion of interdisciplinary research is not new, it has not always been encouraged in academia. Some faculty who go in that direction still worry about whether it will threaten their recognition when applying for grants, seeking promotions or submitting papers to high-impact journals. We are not suggesting that traditional academic departments should be disbanded. On the contrary, they give the required depth to the research, whereas the interdisciplinary team gives breadth to the overall effort.

Our cluster proposal was a success, and in 2019 the National Center for Integrated Coastal Research

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(UCF Coastal) was born. Our goal is to guide more effective economic development, environmental stewardship, hazard-mitigation planning and public policy for coastal communities. To better integrate science with societal needs, we have brought together biologists, chemists, engineers and biomedical researchers with anthropologists, sociologists, political scientists, planners, emergency managers and economists. It seems that the most creative perspectives on old problems have arisen when people with different training and life experiences are talking through issues over cups of coffee. After all, "interdisciplinary" must mean more than just different flavors of STEM. In academia, tackling the effects of climate change demands more rigorous inclusion of the social sciences—an area that has been frequently overlooked.

The National Science Foundation, as well as other groups, has recently required that all research proposals incorporate a social sciences component, as an attempt to assess the broader implications of projects. Unfortunately, in many cases, simply adding a social scientist to a proposal is done only to check a box rather than to make a true commitment to allowing the discipline to inform a project. Instead social, economic and policy needs must be considered at the outset of research design, not as an afterthought. Otherwise our work might fail at the implementation stage, which means we are not being as effective as we could be in solving real-world problems. As a result, the public might become skeptical of how much scientists can contribute toward solutions.

CONNECTING WITH THE PUBLIC

THE REALITY is that communicating research findings to the public is an increasingly critical responsibility of scientists. Doing so has a measurable effect on how politicians prioritize policy, funding and regulations. UCF Coastal was brought into a world where science is not always respected—sometimes it is even portrayed as the enemy. There has been a significant erosion of trust in science over recent years, and we must work more deliberately to regain it. The public, we have found, wants to see quality academic research that is grounded in the societal challenges we are facing. That is why we are melding pure academic research with applied research to focus on issues that are immediate—helping a town or business recovering from Hurricane Irma, for example—as well as long term, such as directly advising a community how to build resiliency as flooding becomes more frequent.

As scientists, we cannot expect to explain the implications of our research to the wider public if we cannot first understand one another. A benefit of regularly working side by side is that we are crafting a common language, reconciling the radically different meanings that the same words can have to a variety of specialists. Finally, we are learning to speak to one another with more clarity and understand more explicitly how our niches fit into the bigger picture. We are also more aware of culture and industry as driving forces in shaping consensus and policy. Rather than handing city planners a stack of research papers and walking away, UCF Coastal sees itself as a collaborator that listens instead of just lecturing.

This style of academic mission is not only relevant to issues around climate change. It relates to every aspect of modern society, including genetic engineering, automation, artificial intelligence, and so on. The launch of UCF Coastal has garnered positive attention from industry, government agencies, local communities and academics. We think that is because people do want to come together to solve problems, but they need a better mechanism for doing so. We hope to be that conduit while inspiring other academic institutions to do the same.

"Interdisciplinary" must mean more than just different flavors of STEM. In academia, tackling the effects of climate change demands more rigorous inclusion of the social sciences.

After all, we have heard for years to "think globally, act locally," and that "all politics is local." Florida's Indian River Lagoon will be restored only if there is engagement among residents, local industries, academics, government agencies and nonprofit organizations. As scientists, it is our responsibility to help everyone involved understand that problems that took decades to create will take decades to fix. We need to present the most helpful solutions while explaining the intricacies of the tradeoffs for each one. Doing so is only possible if we see ourselves as part of an interdisciplinary, whole-community approach. By listening and responding to fears and concerns, we can make a stronger case for why scientifically driven decisions will be more effective in the long run. SA

Graham A. J. Worthy is founder and director of the National Center for Integrated Coastal Research at the University of Central Florida (UCF Coastal) and chairs the department of biology. His research focuses on how marine ecosystems respond to natural and anthropogenic perturbations.

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HOW CITIES COULD SAVE US

Urban areas can improve the planet as well as people's lives if we design them to be much more resourceful with energy, water, food and minerals

By William McDonough

CITIES ARE HOME TO MORE THAN HALF THE WORLD'S population, and they exert increasing stress on the earth. They produce up to 70 percent of global carbon dioxide emissions, use up vast quantities of water, degrade water quality and produce mountains of waste. As cities go, so goes the planet. And cities are growing—fast. By 2030, according to the latest United Nations estimates, five billion people will live in cities, nearly half of them conducting their lives in homes, schools, workplaces and parks that do not yet exist.

The challenges in making cities as sustainable as possible are enormous. But they are also inspiring because cities can play an outsized role in creating solutions for a more sustainable world. Cities are engines of innovation and entrepreneurial energy. As networks of city leaders are showing, municipalities are also powerful actors, pooling their strengths, setting environmental agendas and exercising global leadership. From megacities to towns, mayors and city councils, investors, economists and planners are responding to the urgent need to redesign the basic elements

Illustration by Harry Campbell

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of fast-growing cities from the ground up. How they reimagine the urban landscape and how they design growth will profoundly influence the future of all life on the planet.

Many cities are taking important steps to reduce air and water pollution. They are being "less bad." Efficiency in itself, however, is insufficient to move us to a positive future. If cities can also be effective and do "more good," for example, by converting waste back into nutrients for food production, cities can propel us toward a future we want, not just reduce the impacts we do not want. More good, not just less bad.

A clear vision for reimagining the city and its relationship to its surrounding countryside can be found in replicating the operating system of the natural world. In essence, natural systems operate on the free energy of the sun, which interacts with the geochemistry of the earth to sustain productive, regenerative biological systems. Human systems, including cities, that operate by the same laws can approach the effectiveness of living systems.

These laws can be distilled into three key principles: equate waste with food; maximize use of solar income; and celebrate diversity.

Waste does not exist in nature, because each organism contributes to the health of the whole. A fruit tree's blossoms fall to the ground and decompose into food for other living things. Bacteria and fungi feed on the organic waste of both the tree and the animals that eat its fruit, depositing nutrients in the soil that the tree can take up and convert into growth. One organism's waste becomes food for another. Nutrients flow perpetually in regenerative, cradle-to-cradle cycles of birth, decay and rebirth. Waste equals food.

OUR CITIES ARE CURRENTLY DESIGNED for linear flow. Biological nutrients (such as food and wood) and technical nutrients (such as metals and plastics) enter at one end and are used, then discarded. After waste is sifted for valuable recyclables such as metals, paper and certain plastics, it flows out the other end, headed for landfills or incinerators. The process is "take, make, waste." But just as we have redesigned certain consumer products to be disassembled, recycled or reused, we can design cities in a similar, circular fashion: take, make, retake, remake, restore.

In the circular city, wastes become resources. Consider sewage. In a linear city, wastewater-treatment plants process food residues and human waste—including the valuable minerals they contain, such as phosphate—and release the effluent into rivers as pollution. Farmers then buy more phosphate from Morocco or other distant lands to make new fertilizer to grow more food in soils that have lost those minerals. In the circular city, sewage-treatment plants become fertilizer factories. The carbon, phosphate and nitrogen flowing out of the facility are seen as potential assets for soil, not as liabilities for the nearest river. Circular cities mine the wastewater for phosphate and turn it into fertilizer for parks and vegetable gardens on city rooftops and for farms and forests surrounding the city. This process eliminates the need to buy more phosphate from faraway sources and transport it to the U.S. It also avoids the energy and carbon emissions involved in mining and transport. Ostara Nutrient Recovery Technologies in Vancouver is one of several companies pioneering the collection of the phosphate mineral struvite for fertilizer from sewage sludge.

Eliminating the concept of waste extends to all systems, so circular cities design incoming materials for "next use" instead of "end of life." For example, new technologies allow cell-phone circuit boards to be profitably processed in a clean facility, where all the rare earth minerals and precious metals are recovered for reuse in new electronic products.

A second key principle of nature, and what we might call positive cities, is that everything is powered by the sun—and sometimes, as in the Iceland city of Reykjavík, by geothermal power. Trees and plants manufacture food from sunlight—an elegant, effective system that uses the earth's only perpetual source of energy income. Buildings can tap into solar income by directly converting the sun to energy and by passively collecting the solar radiation for heat and natural lighting. Winds—thermal flows fueled by sunlight—can also be harnessed. Together solar, wind and geothermal energy can generate enough power cost-effectively to meet the needs of entire cities and regions, even nations. Cities such as San Francisco are already making significant progress toward meeting their commitments to run 100 percent on renewable energy in the next 10 years.

The third key principle—diversity—is found in all healthy ecosystems. Each organism has a unique response to its surroundings that works in concert with other organisms to sustain the system. Each organism fits in its place, and in each system the most fitting thrive.

Urban designers aiming for what fits attend carefully to local ecologies. They assess the geology, hydrology, vegetation and climate. They incorporate natural and cultural history. By combining this rich "essay of clues," designers discover appropriate patterns for the development of the landscape. By doing so, they create possibilities for positive growth that supports life.

Ultimately what we want is a city designed to allow people to live and work in the same neighborhood. If residents can decompose cell phones at a clean factory that fits within a city's ecosystem, there is no need to relegate the factory to special zones of bad behavior at the outskirts of town. A positive city eliminates the need for zoning driven by concern about unsafe or unhealthy activities. Factories can be in the middle of clean residential neighborhoods, providing jobs so people can live within walking or biking distance. That opportunity, in turn, greatly reduces the need for commuting and transportation—a huge waste of resources and of people's time. And if fresh, healthy food is grown on rooftops across the city, as Method Products' South Side Soapbox factory in Chicago is doing, not only can local organic waste be a resource for food-growing systems, but people working at the rooftop farms can live locally as well.

Imagine everything we make as a gesture that supports life, inspires delight and finds harmony with nature. Buildings operate like trees: they sequester carbon, make oxygen, distill water, provide habitat for thousands of species, and convert solar income into all the thermal and electrical energy they need—and sell excess power to the neighbors. Buildings with on-site wetlands and botanical gardens recover nutrients from wastewater and clean what remains for on-site kitchens and bathrooms. Fresh air, flowering plants and daylight are everywhere. Buildings and communities function as life-support systems.

With this vision in mind, we can imagine food and materials produced in the surrounding countryside, created with tools and technology made in the city. The city returns waste as a raw material that replenishes the system, putting the "re" back into

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resources. Everything moves in regenerative cycles, from city to country, country to city, in natural and cultural networks that circulate biological and technical nutrition—the hardware and software of the 21st century. The metabolism of a living, positive city allows human settlements and the natural world to flourish together. If we are to make our cities truly sustaining and beneficial for all, we need to take this as a literal, strategic truth that informs all our designs.

It is compelling to lay out principles for a utopian future. But can existing cities actually put them into practice today? Some recent industrial facilities are demonstrating how.

The renovation and expansion of the Ford Rouge Center in Dearborn, Mich., transformed the massive, historic car- and truck-manufacturing complex into a model of industrial sustainability. The master plan incorporated a 10-acre green roof—the heart of a system of wetland gardens, porous paving, hedgerows and bioswales. The project turned a 100-year-old industrial brownfield site into a thriving storm-water ecosystem that captures, cleanses and slowly releases water to the adjacent Rouge River in ways that support watershed health. Native killdeer returned to nest a week after construction was completed.

Another model is Sustainability Base, NASA's center for science and computing at its Ames Research Center in Moffett Field, Calif. The facility has the potential to provide all its heating, cooling and energy needs—and even an energy surplus—from solar and geothermal sources and a fuel cell with advanced energy-management controls. Wastewater is treated on-site.

The award-winning Park 20|20 development in Hoofddorp, the Netherlands, is another model. It is a diverse set of buildings and open spaces now being completed across 28 acres. People can access the park easily by air, rail, bus and bicycle. Green zones, plazas, public gardens and canal boardwalks provide a connection to the larger community. Each building's size, structure and orientation are optimized to capture the sun's energy and light. Buildings across the park integrate energy, water and waste-management systems, acting as a single organism.

CAN WE EXPAND these successes to entire cities? Inspiration comes from some intriguing places. One of them is Curitiba, Brazil.

Curitiba began transforming in the 1970s, under legendary architect and urban planner Jaime Lerner, who was mayor three different times from the 1970s to the 1990s. During his first term Lerner realized that the poor town of several hundred thousand inhabitants needed better public transportation. Because a subway or heavy rail system would cost far too much, he instead asked Volvo to make 270 Swedish articulated buses, done within the city, which gave residents jobs. The city hired locals to build aboveground, street-side bus shelters, or *tubos,* from which people could travel anywhere for a flat fare. Instead of riders paying with a token as they boarded a bus, a slow process, Lerner had them prepay when entering the *tubo* platform, so when the bus arrived, they could get on quickly, reducing loading time and making the entire system efficient.

As a result of Curitiba's rapid population growth, garbage was piling up in narrow alleyways where trucks could not retrieve it. Lerner created a program to instruct children how to separate trash, then sent them home to teach their families. In exchange for the sorted garbage, people were paid in bus tokens or fresh food; Lerner paid them in a currency for mobility. Suddenly, everyone was using mass transit. Today up to 85 percent of Curitiba citizens use the bus, and 90 percent recycle. Curitiba recycles 70 percent of its refuse—one of the highest rates in the world.

World population living in cities: **56%**

5 Billion

People living in cities by 2030

U.S. cities committed to 100% renewable energy:

>170

Residents who use the bus in Curitiba, Brazil:

85%

This innovative thinking went on and on. Instead of building a big central library downtown, the city created a network of 50 small "Lighthouses of Knowledge" throughout the neighborhoods so that every child was within walking distance of a library. Local builders, of course, constructed the brightly colored buildings. The libraries work with municipal schools and offer thousands of books and free Internet for citizens ages three to 80. These and other steps transformed the city to a live-work design.

Now imagine if Manhattan had this same kind of vision—with local food growing on the rooftops of hundreds of schools and hospitals, providing nutrition as well as local jobs. Kids could use their optical sensors known as eyeballs to sort trash, pull out the plastics, bring them to recycling centers so they do not end up in the ocean and then get paid in toys. Clean factories would reformulate the plastics into monomers that can be used again. Everything is powered by the sun, and materials flow in continuous cycles of biological and technical nutrition.

What we are after, for all people, is something I would call the "good life"—a life that is safe, dignified and creative. Positive cities are the places where that can happen. If they are designed and run on this principle, everything gets better. We have to insist on the rights of humanity and nature to coexist, to bring together the city and its surrounding countryside.

Cities are designed, but they are also organisms. As French anthropologist Claude Lévi-Strauss pointed out years ago, cities are "something lived and something dreamed." As makers of living places, we cannot help projecting ourselves onto the landscape. But as we dream of our ideal cities, as we conjure the human weft on the geologic warp of the land, we can begin to see more clearly the true character of the place we inhabit, its spirit. Then, as we shape the nature of our cities, we will be making places that celebrate both human creativity and a rich, harmonious relationship with the living earth. We will be forging a new geography of hope. SA

William McDonough is an architect who has pioneered design for sustainable development. He is founder of William McDonough + Partners and McDonough Innovation and co-founder of the Cradle to Cradle Products Innovation Institute.

Sources: The World's Cities in 2016: Data Booklet. United Nations, 2016 (*population in cities now and in 2030*); Sierra Club (*U.S. cities committed to renewable energy*); Low Carbon Green Growth Roadmap for Asia and the Pacific. United Nations Economic and Social Commission for Asia and the Pacific. U.N., 2012 (*bus use in Curitiba, Brazil*)

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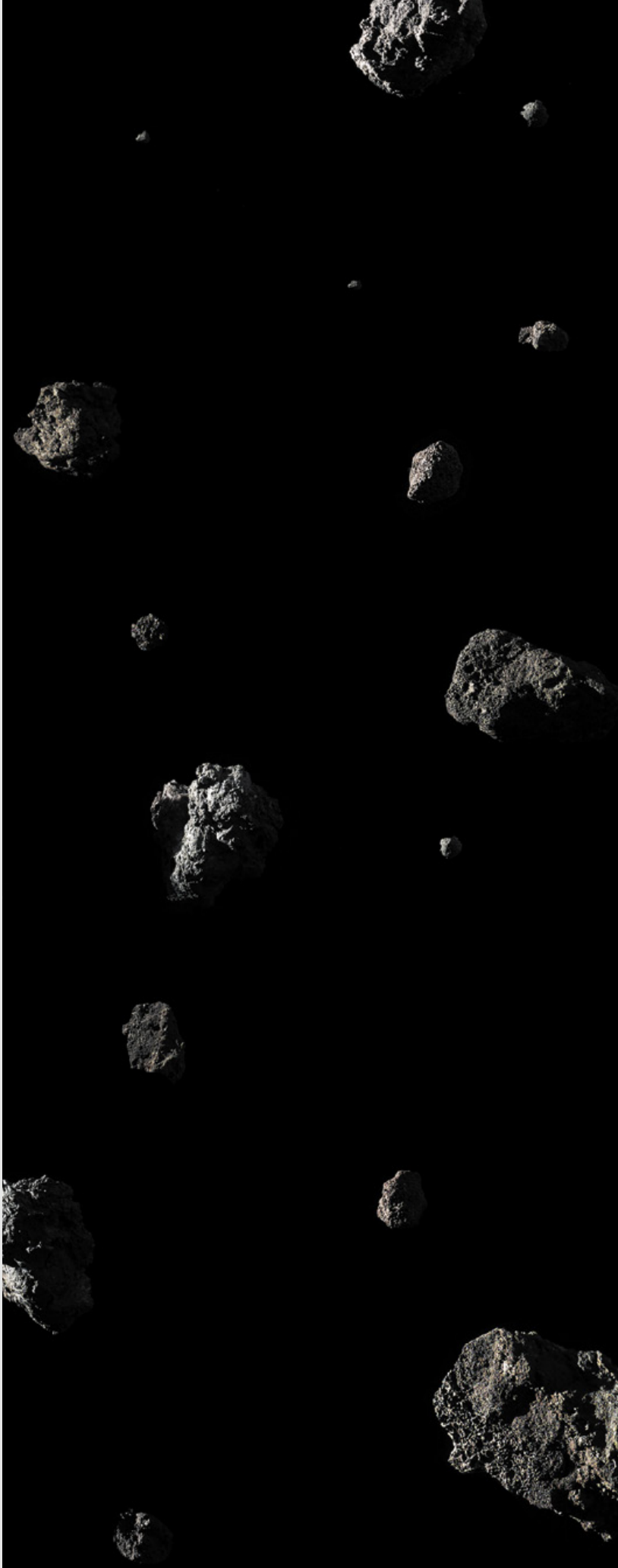
DEEP TIME, DEEP SURVIVAL

How long will we last?

By David Grinspoon

Photograph by Andrew Myers



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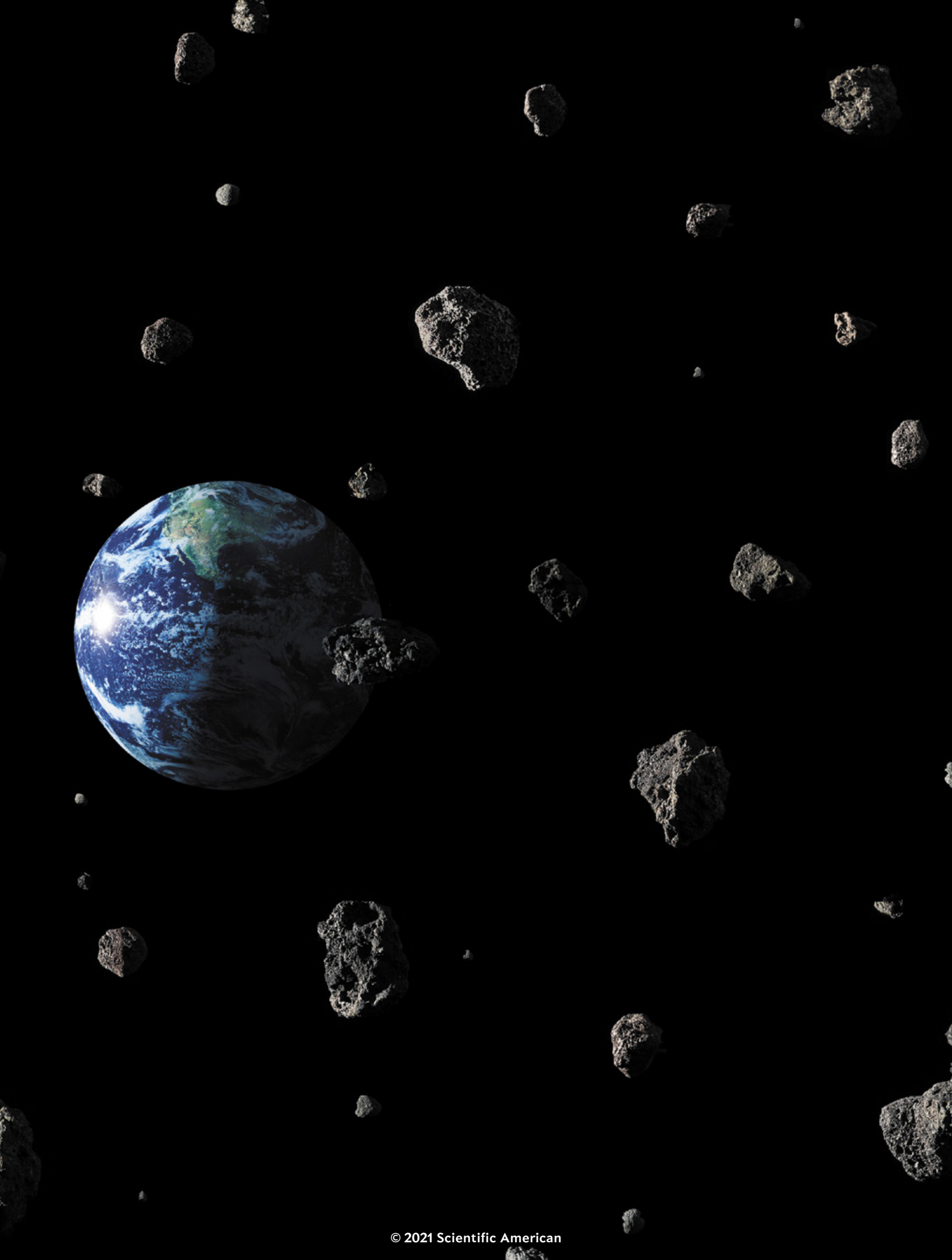

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THE BIGGEST DEBATE AMONG EXPERTS ON THE ANTHROPOCENE IS WHEN, exactly, a geologic epoch marked by humanity's influence began. As an astrobiologist who studies major historical transitions in planetary evolution, I am more interested in another question: When, and how, will the Anthropocene end?

Epochs are relatively short periods of geologic time. Much more consequential are the boundaries separating the geologic timescale's longest phases, the billion-year-scale chunks of history called eons. These transitions left the world permanently and profoundly changed. From the hellish conditions of the Hadean eon, Earth shifted to a cooler, quieter Archean eon that nurtured the emergence of life. During the Proterozoic eon, some of those microbes became a disruptive, planet-altering force, flooding the atmosphere with photosynthetic oxygen. This change in atmospheric chemistry poisoned much of the biosphere, but it also led to the flourishing of complex multicellular life, ushering in our current eon, the Phanerozoic.

The Anthropocene may be the beginning of another fundamental transition. This fifth eon could be defined by a radically new type of global change in which cognitive processes—the thoughts, deeds and creations of human beings—become a key part of the functioning of our planet. I propose we call this potential new eon the Sapiezoic, for "wise life." For the first time in Earth's history, a self-aware geologic force is shaping the planet.

But an epoch only becomes an eon if it endures for hundreds of millions of years or longer. For that to happen, *we* have to endure that long. Are we up to it?

AVOIDING EXTINCTION

OUR MOST IMMEDIATE challenges over the next century are to stabilize our population and to construct energy and agricultural systems that can provide for us without wrecking natural systems. There is no doubt that we will shift away from fossil fuels, but the speed with which we do so may determine whether the displacement and suffering caused by climate disruption in the 21st century will rival or surpass those caused by the wars, revolutions and famines of the 20th.

Anthropogenic global warming is waking us up to our inescapable role as planetary-scale operators, but it is not the only large-scale, long-term challenge we will face. Over the coming centuries, for example, we will need to devise effective defenses against dangerous asteroids and comets. A much smaller object than the 10-kilometer rock that did in the dinosaurs could devastate human civilization. Soon we will have catalogued most of the dangerous Earth-crossing asteroids. But a dark and dangerous comet can always come screaming from the fringes of the solar system with little warning. We should be ready to deflect such an interloper.

On a longer timescale—tens of thousands of years—we must learn how to prevent natural climate changes that dwarf the present warming spike. Civilization has developed during what is essentially a 10,000-year summer, a multimillennial period of unusually warm and stable climate. This will not last—unless we decide it should. Over tens of thousands to many millions of years, Earth goes through

WHAT IS THE CHANCE *HOMO SAPIENS* WILL SURVIVE FOR THE NEXT 500 YEARS?

"I would say that the odds are good for our survival. Even the big threats—nuclear warfare or an ecological catastrophe, perhaps following from climate change—aren't existential in the sense that they would wipe us out entirely. And the current bugaboo, in which our electronic progeny exceed us and decide they can live without us, can be avoided by unplugging them."

Carlton Caves
Distinguished Professor Emeritus in physics and astronomy at the University of New Mexico

Prop Styling by **Angela Campos** *Stockland Martel (preceding pages)*

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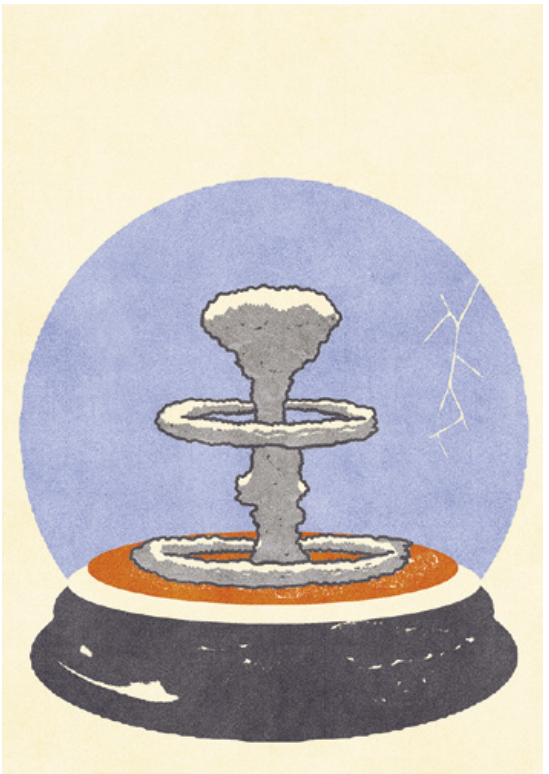

ARE WE ANY CLOSER TO PREVENTING NUCLEAR HOLOCAUST?

Since 9/11, the U.S. has had a major policy focus on reducing the danger of nuclear terrorism by increasing the security of highly enriched uranium and plutonium and removing them from as many locations as possible. A nuclear terrorist event could kill 100,000 people. Three decades after the end of the cold war, however, the larger danger of a nuclear holocaust involving thousands of nuclear explosions and tens to hundreds of millions of immediate deaths still persists in the U.S.-Russian nuclear confrontation.

"Remembering Pearl Harbor, the U.S. postured its nuclear forces for the possibility of a bolt-out-of-the-blue first strike in which Russia would try to destroy all the U.S. forces that were targetable. We don't expect such an attack today, but each side still keeps intercontinental and submarine-launched ballistic missiles carrying about 1,000 warheads in a launch-on-warning posture. Because the flight time of a ballistic missile is only 15 to 30 minutes, decisions that could result in hundreds of millions of deaths would have to be made within minutes. This creates a significant possibility of an accidental nuclear war or even hackers causing launches.

"The U.S. does not need this posture to maintain deterrence, because it has about 800 warheads on untargetable submarines at sea at any time. If there is a nuclear war, however, U.S. Strategic Command and Russia's Strategic Missile Forces want to be able to use their vulnerable land-based missiles before they can be destroyed. So the cold war may be over, but the Doomsday Machine that came out of the confrontation with the Soviets is still with us—and on a hair trigger."

Frank von Hippel
Emeritus professor at the Princeton School of Public and International Affairs and co-founder of Princeton University's Program on Science and Global Security

cycles of glaciation and global warming. Another ice age would wipe out most of our agriculture and thus our civilization while causing the extinction of countless other species. Geoengineering techniques to artificially cool (or heat) the planet could free the Sapiezoic eon from these destructive fluctuations in climate.

Most discussions of geoengineering center on desperate short-term fixes for our self-inflicted climate woes, but our present ignorance of the complexities of Earth's climate makes such attempts exceedingly risky. Geoengineering is best regarded as a long-term project for the distant future, when we know much more about the Earth system and when that system will be pushed to the brink either by intrinsic climate fluctuations or—much further still in the future—by our home star reaching its senescence.

Stars like the sun grow more luminous as they age, meaning that a few billion years from now, our oceans will boil away like Venus's did billions of years ago. Fortunately, this is a long way off. Provided we overcome nearer-term existential threats, we will have plenty of time to work on that problem. Perhaps we could somehow rejuvenate the sun, move Earth to a wider orbit or partially shade our planet. Alternatively, we may decide to emigrate to another, younger star system.

THE WORLD IN OUR HANDS

IF INTELLIGENCE CAN ARISE as a self-aware geologic force here, then it can probably emerge elsewhere. As we peer deeper into the universe, we may find that there are three kinds of worlds: dead, living and sapient. Of course, there is a chance that ours is the only sapient world in a vast and silent cosmos. If so, then in addition to shaping the well-being of all future life on Earth, our choices dictate the fate of all sentient life in the universe. That is quite a responsibility.

History offers hope that we can handle it. One of humanity's most ancient hallmarks is our capacity to respond to existential threats. We seem to have survived a genetic bottleneck around 75,000 years ago, when climate change, probably caused by a "volcanic winter," led to the death of most humans. Earlier, between 200,000 and 160,000 years ago, anatomically modern humans arose in Africa after a devastating ice age almost eradicated all our predecessors. The secret to our ancestors' survival was probably our use of language to develop new modes of social cooperation.

Right now we are struggling to find our way through a dawning Anthropocene. If we endure, however, we could learn to protect Earth's biosphere almost indefinitely. In the long run, we could prove to be the best thing that ever happened to planet Earth. SA

David Grinspoon is a senior scientist at the Planetary Science Institute in Tucson, Ariz. In 2012 and 2013 he served as the U.S. Library of Congress's first chair of astrobiology while researching his book *Earth in Human Hands: Shaping Our Planet's Future* (Grand Central, 2016).

Illustration by Lorenzo Gritti, Portraits by Kyle Hilton

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Rethinking the "Anthropocene"

A popular name for our era perpetuates misperceptions about humans and nature

By the Editors

Alarming news, arriving almost daily, about rising temperatures, melting glaciers, species diebacks, radioactive waste, oceans contaminated with plastic, and other calamities has seared in our minds the staggering impact that humanity now has on our planet. The late atmospheric scientist Paul Crutzen encapsulated these concerns into a single word, the "Anthropocene," which he proposed in 2000 as the geologic name of an era dominated by the human race. Geologists cannot agree on when the Anthropocene began, and stratigraphers are still debating whether it is in fact a geologic era at all. Even so, the term has riveted public attention and sparked impassioned arguments about the relationship between humans and the natural world.

Several scholars in the humanities criticize the name itself, however, arguing that it perpetuates long-standing misconceptions about this relationship. Replacing "Anthropocene" with a name that focuses instead on its underlying causes might be more conducive to helping us tackle them.

One problem with the term is hubris: naming a geologic era after ourselves suggests a certain awe at our own magnificence. And sociologist Eileen Crist holds that it was such an anthropocentric worldview that got us into this predicament in the first place. When scientists discuss possible responses to a rapidly warming planet, they almost always accept the dominion of humans over all other species, Crist and others charge, imagining that the enlightened among us can sagaciously steer planet Earth onto a sustainable pathway without major disruptions to our modern ways of life.

A second indictment is that "Anthropocene" implicitly blames the entire human race for a crisis caused by a relative few. Surely the "Man of the Hole," the last survivor of an uncontacted hunter-gatherer tribe in the Brazilian Amazon, bears less responsibility for our present predicament than, say, former Secretary of State Rex Tillerson, who was CEO of ExxonMobil. The tribe's carbon emissions are essentially zero, whereas ExxonMobil is the fourth-largest emitter worldwide among fossil-fuel companies, according to Carbon Majors data through 2018.

Yet another critique is that the "Anthropocene discourse" tends to hold not only all humans but *human nature* responsible for this predicament. That makes little sense to anthropologists, who point out that people have repeatedly figured out how to live within their ecological means and even thrive. Social scientists and others contend, however, that the environmental issues we face derive not from human nature but from culture: specifically, a socioeconomic configuration that arose in Europe in the second half of the past millennium. Giving the period a name that focuses on its actual historical and cultural roots, they say, would help us understand what happened, remind us that it is a choice—not an inevitability—and perhaps offer a way forward that does not require sacrificing the glorious wealth of life that surrounds us.

To this end, thinkers have suggested an astonishing variety of alternative names. The most widely accepted is "Capitalocene," first proposed by human geographer Andreas Malm, who locates the origins of the "era of capital" in the use of coal to fuel factories in 19th-century England. In contrast, geographer and historian Jason W. Moore contends that the Capitalocene arose in 15th-century Europe with an economic system predicated on perpetual territorial expansion. Expanding to the New World and moving on to colonies and dominions in Asia, Africa and Australia, capitalism established global systems of manufacturing and trade that consumed nature at unprecedented rates and is only now bumping up against planetary boundaries. Philosopher Donna Haraway has proposed another name that looks to the future: "Chthulucene" (from the Greek *chthonos,* meaning "of the earth"), an age in which we humans teach ourselves to live in full and rich harmony with our fellow beings.

These thinkers seek not so much to dethrone the concept of the Anthropocene as to—perhaps by taking a page from the idea of the Chthulucene—enrich the ongoing discussion between scientists and society to support us all in making the difficult choices ahead. We welcome that idea. Working collaboratively, the natural sciences and the humanities can help us break through thought barriers and generate fresh ideas. To quote Albert Einstein: "We cannot solve our problems with the same thinking we used when we created them." SA

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